Analysis of thermal comfort in a complex atrium under current and future climatic conditions:

Case Study Paul O'Gorman building, UCL.

by

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ABSTRACT

Because of their multiple functions atria have become very popular among low-energy buildings. In terms of energy efficiency their most significant function is probably their ability to induce stack ventilation and act as a buffer zone for surrounding offices.

The purpose of this study was to investigate the thermal performance of a naturally ventilated case study atrium under current and future climatic conditions and their impact on thermal comfort. Thermal comfort conditions under current climatic conditions was estimated through field measurements of Dry Bulb Temperature (°C) and Relative Humidity (%) while possible impacts of global warming were estimated through analysis of dynamic simulation results from TAS with the help of a DSY (Design Summer Year) weather file.

In order to understand better the effect of several design characteristics on the thermal performance of the atrium, different simulations were run in TAS initially including and afterwards lacking those design characteristics. The characteristics found significant to be studied in the certain way involved the large internal gains occurring from the basement plant room and the protection border around the café area. Conclusions on the effect of the café entrance on thermal conditions in the atrium were drawn from a single simulation as it was allowed to do so by its operation schedule.

What occurred from this study is that the café area of the atrium space does overheat and this tendency will increase significantly in the future. To the overheating, the gains occurring from the plant room have the most critical contribution. However, even though ambient temperatures might seem high, the corresponding dry resultant temperatures that are closely related to thermal comfort, are reduced by the enhanced air flow resulting from the excess heat gains from the basement plant room. Their existence helps maintain internal temperatures higher than external during hot spills thus maintaining the stack for longer.

In reducing overheating in the café area the protection border also contributes positively. The stack and therefore air flow are strong because of the excess gains of the plant room and the large air intake, but the protection border manages to prevent warm buoyant air from the basement to enter the café area. Also, the café entrance, when opened, provides an extra air flow into the atrium space that increases the cooling capacity of ventilation.

During heating season the buffer zone formed by the atrium space is responsible for maintaining internal temperatures over the often very low external temperatures. In fact, the heat gains from the plant room provide heating to the unconditioned atrium that not only make thermal comfort conditions bearable in the café area but also help reduce heating energy demand for the surrounding offices. However, the protection border of the café prevents the weak warm buoyant air flow from entering the café area and provide heating effectively.

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Chapter 1

1.0 Introduction

From the industrial revolution and onwards human activities have released gases to the atmosphere that in our days prove to have caused serious changes to the earth's climate. As a result of climate change, the cooling needs of the UK, a once heating dominated country, are expected to increase dramatically over the next decades.

The increase of anthropogenic CO_2 emissions is due primarily to fossil fuel use and the built environment sector is responsible for a large percentage of carbon emissions as obtained from figure 1.

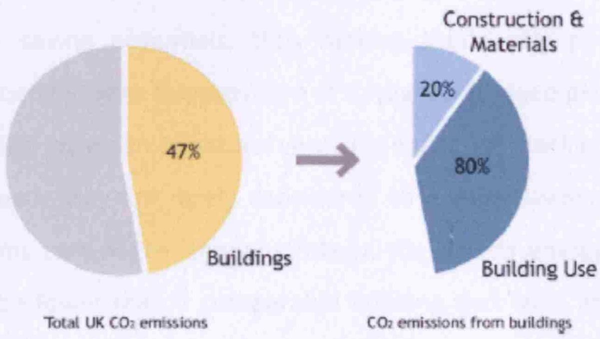

Figure 1. UK CO_2 emissions from building industry (fontenergy, 2007)

Following the trend and legislation on energy efficiency, building industry has transformed dramatically in an effort to purge from high dependence on building services like HVAC systems and artificial lighting and is gradually returning to traditional means of passive heating and cooling and natural ventilation. It is possible to make good-performing naturally ventilated buildings if the location's climate and building use is understood well. However, climate change is making designers' task more difficult as consideration needs to be given not only to the current climatic conditions but also to the ones to come.

Even though naturally ventilated buildings deliver more variable air temperatures the perception of thermal comfort in them during summer can be enhanced by means of enhanced air flow and/or radiant cooling from the building fabric. Furthermore, the occupants of naturally conditioned buildings turn out to be more active in thermoregulatory adaptation through changes in activity level and clothing (behavioral adaptation), and appear more tolerant to a wider range of temperatures (psychological adaptation) (de Dear, 2004 cited in van Hoof & Hensen, 2007) thus increasing natural ventilation opportunities.

In order to cover these issues new Adaptive Models were developed in the past years that give good predictions for buildings without mechanical cooling. These models predict the thermal conditions under which people are expected to be comfortable in buildings rather than their comfort responses (Awbi, 2002). According to CIBSE Guide A (CIBSE Guide A, 2006) the adaptive approach is a "behavioral approach" which studies the way people in their everyday life tend to adjust themselves and their environment, when necessary and/or possible, to increase their feeling of comfort.

Atria among the social benefits that they provide involving stimulation of social activities they also provide energy saving potentials, thus making them very popular. Energy saving opportunities are associated with the provision of daylight into deep plan spaces, the forming of a buffer zone and the provision of natural ventilation through stack effect (Gocer, Ozkan & Tavil, n.d.). Even though they are rarely considered as energy saving features, in buildings where an atrium forms part of the energy strategy, the overall energy consumption of the building is found to be lower than a comparable building that lacks an atrium space (Mills, 1994). However, during hot spills the stack in the atrium can be reversed or eliminated thus reducing provisions of adequate ventilation rates and perception of cooling through air flow.

Because of the complex thermal phenomena and air stratification during summer the thermal and energy performance estimation of atrium buildings becomes a difficult task (Gocer, Ozkan & Tavil, n.d.). Simulation software programs based on numerical solution of equations of heat transfer in buildings with sequences of real data (CIBSE AM10, 2005), are used to help overcome such difficulties.

Chapter 2

2.0 Human Comfort in Naturally Ventilated Buildings

In modern societies people spend more than 90% of their time inside an artificially created 'internal' or 'indoor' environment (a dwelling, an office space, a transport vehicle). As a result of the energy-saving measures which started in the early 1970's these environments have undergone essential changes to achieve energy efficiency and thermal comfort on the same time (Awbi, 2002).

When designing a ventilation system for a room or a building the two factors that affect the microclimate, thermal comfort and indoor air quality, should be considered as they are critical to the well-being of occupants and/or the performance of industrial processes within these spaces (Awbi, 2002). If a building is well designed, natural ventilation is possible to be applied. This ventilation mode takes advantage of natural driving forces such as wind and buoyancy and is useful not only for achieving adequate ventilation rates but also for providing cooling through ventilation.

Because of the variability of external weather conditions, natural ventilation relies on the occupants' adaptive opportunity and therefore has a wider acceptable temperature band that increases natural ventilation opportunities.

2.1 Factors that Affect Thermal Comfort

According to ISO 7730 (ISO, 2004) thermal comfort is 'that condition of mind which expresses satisfaction with the thermal environment'. It can be influenced by environmental and/or personal factors. CIBSE (CIBSE Guide A, 2006) suggests that the environmental factors are:

- Air temperature
- Mean radiant temperature
- Relative air speed
- Humidity

while the personal factors are:

- Metabolic heat production
- Clothing.

2.2 Dry Resultant Temperature (t_{res})

According to Chadderton (Chadderton, n.d.) dry resultant temperature is defined as the temperature recorded by a thermometer at the center of a blackened globe of diameter 100 mm. CIBSE defines dry resultant temperature as:

$$t_{res} = [\, t_r + t_a (10U)^{1/2} \,] \,/\, [\, 1 + (10U)^{1/2} \,], \qquad (1)$$

where U=air speed (m/s)

t_r=mean radiant temperature (°C)

t_a=air temperature (°C)

For still air conditions of U < 0.1 m/s this equation reduces to:

$$t_{res} = 0.5 \,(\, t_r + t_a \,) \qquad (2).$$

Dry resultant temperature is critical in establishing acceptable thermal comfort conditions. For example, if an office building with openable windows and exposed concrete floor soffits has a mean radiant temperature of 20°C, and the air temperature in the space is 28°C, then the perceived temperature (dry resultant temperature) in the space will be 24°C. While an air temperature of 28°C would be considered unacceptable, a dry resultant temperature of 24°C would be perceived as tolerable on a hot summer's day (Beggs & Moodley, 2008).

2.2.1 Comfort Expectations in Naturally Ventilated Buildings During Cooling Season

Although the use of fabric thermal storage does not produce air temperatures as low as the ones achieved with mechanical cooling plants, comfort in occupied spaces is possible by improving the mean radiant temperature and air movement. On comfort of the performance of passively cooled spaces Clark (Clark, 1989 cited in CIBSE RR6, 1998) concluded that:

- At low air speeds, comfort is sensitive to the mean temperature of the space
- At high air speeds, air temperature dominates comfort perception
- Air motion can produce comfort at air temperatures exceeding 29,4 °C
- Comfort imposes a lower limit on floor temperatures and an upper limit on the non-uniformity in the mean radiant temperature with ankle to neck vertical air

temperature smaller than 3 ^{0}C, vertical direction radiant asymmetry less than 5 ^{0}C and in the horizontal plane 10 ^{0}C

As shown in figure 2 an air flow of about 0.25 m/s is enough to provide a cooling effect equivalent to 1 K reduction in dry resultant temperature (CIBSE AM10, 2005). However, note that temperatures greater than 0.3 m/s are accepted only during summer.

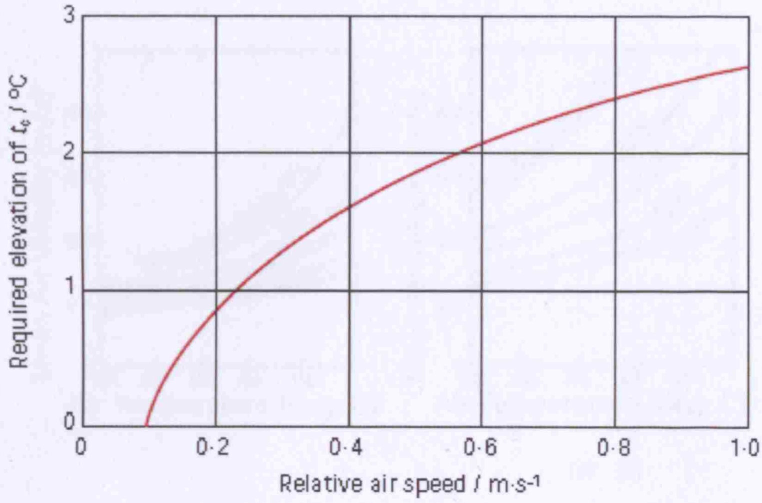

Figure 2. Effect of air speed on dry resultant temperature (CIBSE Guide A, 2006, p. 1-4)

Therefore, even though naturally ventilated buildings deliver more variable air temperatures the perception of thermal comfort in them during summer can be enhanced by means of enhanced air flow and/or radiant cooling from the building fabric. However, consideration has to be given to the sizing and positioning of such openings so as to avoid nuisance draughts that could for example blow papers of desks (CIBSE AM10, 2005).

2.2.1.1 Thermal Storage

High admittance buildings have the ability to absorb heat energy, thus reducing surface temperatures. As a result there is less need to dispose heat gains as they occur. By exposing the "mass" of a building it is possible to reduce the mean radiant temperature within the space, and thus the dry resultant temperature (Beggs & Moodley, 2008).

The most efficient way to accomplish low surface temperatures is through night ventilation and it is analyzed further below.

2.2.1.2 Draught Risk

According to H. B. Awbi (Awbi, 2002) draught is defined as an undesired local cooling of the human body caused by air movement. During summer though, draughts can produce a cooling effect to the skin by convection, depending on the temperature difference between the air and skin, air speed and the magnitude of the fluctuations in the air speed i.e. turbulence level.

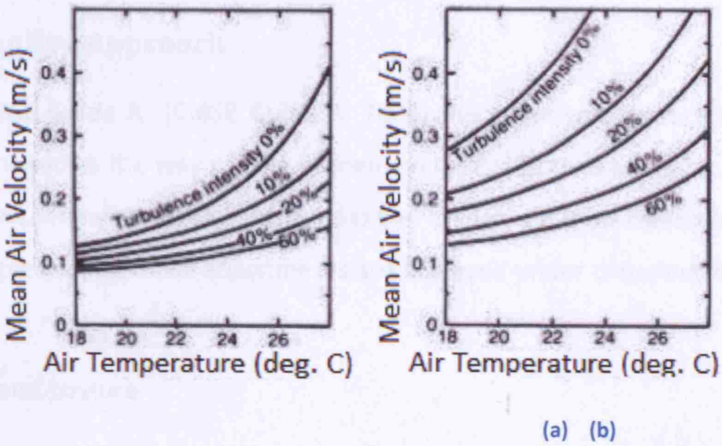

Figure 3. Relationship between mean air speed and temperature for different values of turbulence intensity to produce 10% and 20% dissatisfied as a result of draught: (a) 10% dissatisfied and (b) 20% dissatisfied (Awbi, 2002, p. 35)

According to Chadderton (Chadderton, n.d.) variable air velocity and direction are preferable to unchanging values. Therefore, slightly higher air speeds could be accepted for naturally ventilated buildings as a result of fluctuating natural driving forces.

2.3 Adaptive Models

Adaptation is defined as the gradual lessening of the human response to repeated environmental stimulation (de Dear et al, 1997 cited in van Hoof & Hensen, 2007), and can be both behavioral, physiological as well as psychological (de Dear et al, 1997, 1998, 2002 cited in van Hoof & Hensen, 2007). New Adaptive Models have been developed over the past years that predict the thermal conditions under which people are expected to be comfortable in free-running buildings rather than their comfort responses (Awbi, 2002).

Adaptive methods' have recently managed to correlate the running mean of the weekly but also daily mean outdoor temperatures with the comfort temperature. As suggested by

McCartney and Nicol (McCartney & Nicol, 2002 cited in Nicol & Pagliano, 2007) this linear relationship for European offices is given by the formulae:

$$t_c = 0.33\ t_{rm} + 18.8 \qquad (3)$$

where: t_c = the optimal operative temperature for comfort
t_{rm} is the running mean of the daily mean outdoor temperature.

2.3.1 The Adaptive Approach

According to CIBSE Guide A (CIBSE Guide A, 2006) the adaptive approach is a "behavioral approach" which studies the way people in their everyday life tend to adjust themselves and their environment, when necessary and/or possible, to increase their feeling of comfort. Awbi (Awbi, 2002) suggests that these adjustments are achieved under conscious control and may involve:

- Activity and posture
- Clothing
- moving between building thermal zones
- thermal environment.

According to Awbi (Awbi, 2002) adaptation is also time-dependent e.g.

- short-term: adjustment in clothing, posture and thermal environment
- long-term: seasonal changes in clothing and/or activity, changes in furnishing and building control devices

The success of a natural ventilation strategy in buildings relies on the occupants' tolerance to varying environmental conditions and to their will and ability to adjust to the changing thermal environment.

2.5 Overheating Risk

Unlike occupants of air-conditioned buildings, occupants of naturally conditioned buildings turn out to be more active in thermoregulatory adaptation through changes in activity level and clothing (behavioral adaptation), and appear more tolerant to a wider range of temperatures (psychological adaptation) (de Dear, 2004 cited in van Hoof & Hensen, 2007).

In the UK, research (CIBSE Guide A, 2006) has found that in summer 25 ^{0}C is an acceptable indoor dry bulb temperature for free running (i.e. non-air conditioning) office buildings. A benchmark maximum of 28 ^{0}C is given over which the comfort, and therefore productivity of building occupants, is significantly reduced. The frequency of occurrence of this benchmark in naturally ventilated buildings must not exceed 1% of occupied hours yearly, while 25 ^{0}C must not be exceeded for over 5% of that same time.

Chapter 3

3.0 Atria and Natural Ventilation

Even though atria as spaces are rarely considered as energy saving features, in buildings where an atrium forms part of the energy strategy, the overall energy consumption of the building is found to be lower than a comparable building that lacks of an atrium space (Mills, 1994). In our days, the need for significant reductions in building energy consumption has made atria very popular among architects and engineers and have become a successful solution in commercial and institutional multistory buildings where large spaces are provided for various purposes (Kainlauri & Vilmain, 1993). The technical reasons for this involve the ability of atria to:

- act as a buffer zone
- favor stack and wind ventilation
- increase natural lighting opportunities.

Nonetheless, efficient natural ventilation strategies are only achieved when the geometry and the openings are designed carefully to fulfill required ventilation rates and control needs (Andersen, 2005).

Atria are also popular both among occupants and architects as they form the social centre of buildings. On atria, the Dragvoll survey (Cold, 1985 cited in Bryn, 1995), concluded that:

- Atria and semi-climatized zones stimulate social activities
- Service functions in atria create greater activity in them
- It is possible to make attractive offices or study areas directly connected to atria
- There are no technical problems in providing good daylight in atria
- The climate in atria promotes rich and varied plant growth

3.1 History

Atria first became popular in Europe in the Industrial Revolution when builders wanted to display their skills in creating new, exciting iron and glass constructions. In those pre-electricity days large glazed roof-lights over deep plan buildings provided adequate lighting to commercial enterprise. Heating opportunities were provided to these spaces by steam-based heating systems. Rich upper and middle classes had the opportunity to "promenade" all year in untreated sunspaces that often had the character of a garden protected from adverse climatic conditions (Mills, 1994). In fact, many private atrium-gardens were built during that period in which intellectual conversations took part.

At the end of the Victorian period the lack of economic resources but also the development of electricity and more recently the development of mechanical ventilation caused the declension of atria. Buildings were now built with little consideration on the sizing and orientation of openings as internal environments could be improved by non-natural means. However, these buildings have been regarded by their occupants as uncomfortable, inflexible, unable to cope with modern office technology and costly to run (Mills, 1994).

In recent days where tackling of climate change is one of humanity's most critical concern energy efficient buildings and thus atria have once again become very popular. Governments are making a significant effort in promoting passive design principles but still, building regulations and definitive design guidance on atria are insufficient. The flexibility to locate the atrium to maximum advantage for ventilation purposes is often restricted, by the multi-functional nature of atria since many other criteria now have to be satisfied. Therefore, even if energy conservation may dictate some design criteria, other considerations, such as profitability, productivity and convenience, often determine the decision-making process (Kainlauri & Vilmain, 1993).

3.2 Definition of Atria

Atria are large glazed spaces attached to a building or placed between two or more buildings. They are thermally separated from the buildings they are connected to and very often they are partially heated or not heated at all (EASE, n.d.).

3.2.1 Atrium Building Typology

The IEA project, Passive and Hybrid Solar Commercial Buildings defines a typology for atrium building shown in figure 4 (Bryn, 1995).

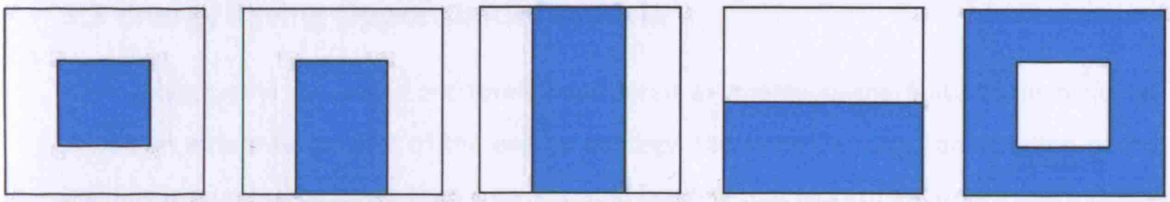

Figure 4. Building typologies: core, integrated, linear, attached, envelope (Hastings, 1992 cited in Bryn, 1995)

The core, integrated and linear type are commonly used as heated without too much energy atria while the attached and envelope type are unheated atria but still contributing to the heating energy consumption of the building. Very often buildings are characterized by a combination of these typologies as their form is not always clear (Bryn, 1995).

3.2.2 Energy Balance of Atria

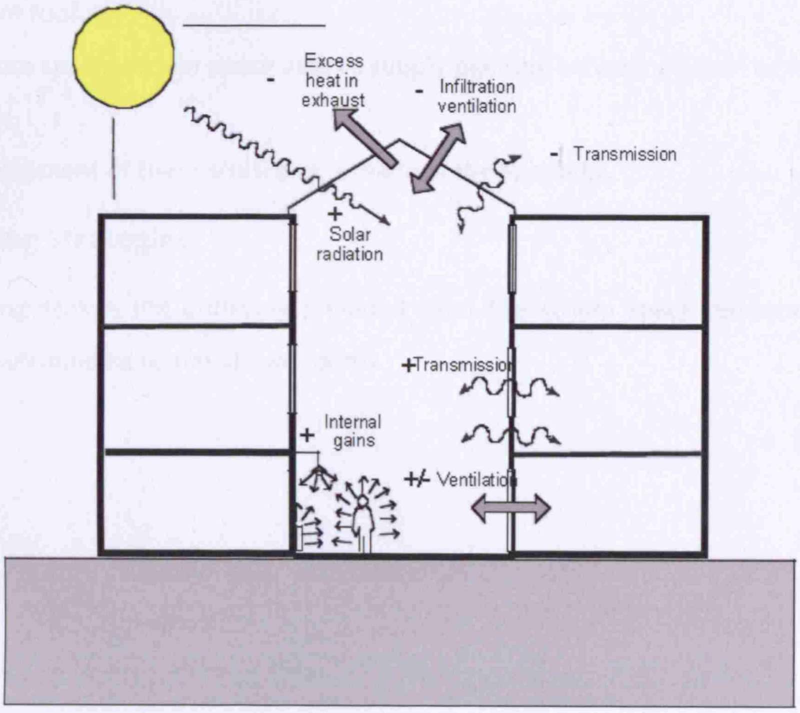

Figure 5. The energy balance of an atrium (EASE, n.d.)

In an unconditioned atrium the temperature depends mostly on transmission losses through the envelope, on solar gains through the glazed surfaces and on internal gains occurring from occupants, equipment and artificial lighting as illustrated in figure 5.

3.3 Energy Saving Opportunities in Atria

Even though atria as spaces are rarely considered as energy saving features, in buildings where an atrium forms part of the energy strategy, the overall energy consumption of the building is found to be lower than a comparable building that lacks of an atrium space (Mills, 1994). According to Mills (Mills, 1994) the most critical energy-saving strategies that can be applied to atria involve:

- Lighting: atria provide opportunity for daylight penetration into deep plan buildings.
- Buffer space (insulation): atria act as a large habitable insulation layer between their host buildings and the outside.
- Natural ventilation: atrium spaces are often used to induce air movement from the external facades to the inner face and subsequently exhaust that air through the atrium roof.
- Plenum space: atrium space acts as supply plenum, exhaust plenum or heated buffer space.

Further development of these strategies is made in the appendix.

3.3.1 Heating Strategies

During heating season the buffering provided from the atrium space reduces the heating demand for surrounding to the atrium rooms.

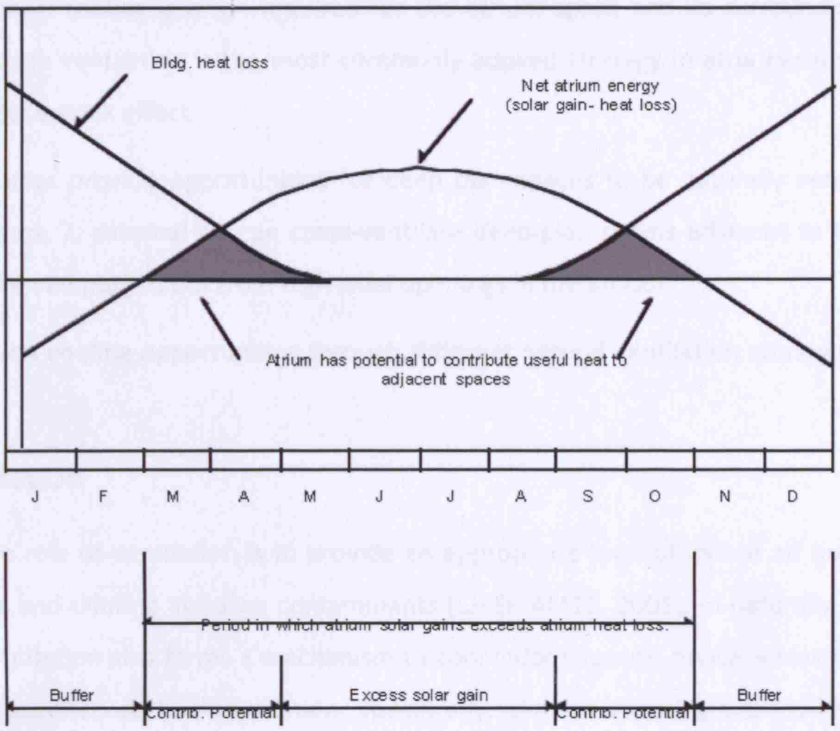

Figure 6. Passive heating potential of atrium buildings (Hastings, 1992 cited in EASE, n.d.)

As observed in figure 6, during mid-season solar gains are higher than heat losses in the atrium space and can even provide adjacent spaces with heating. This happens because solar gain is higher than heat losses thus providing a useful net heat gain.

3.3.2 Cooling Strategies

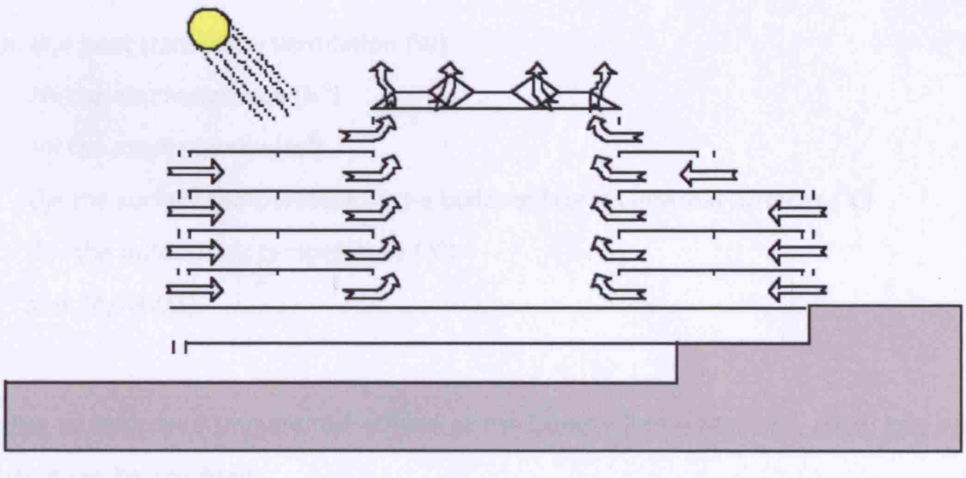

Figure 7. Cooling through natural ventilation (Hastings, 1992 cited in EASE, n.d.)

During summer, cooling is often required for the atrium space and its surrounding spaces. Cooling through ventilation is the most commonly applied strategy in atria because of their ability to induce stack effect.

Atrium buildings provide opportunities for deep plan spaces to be naturally ventilated. As shown in figure 7, external air can cross-ventilate deep-plan rooms adjacent to the atrium space and then be purged out from high level openings in the atrium.

More detail on cooling opportunities through different natural ventilation strategies is given below.

3.4 Ventilation

The principle role of ventilation is to provide an appropriate level of indoor air quality (IAQ) by removing and diluting airborne contaminants (CIBSE AM10, 2005). In naturally ventilated buildings ventilation also forms a mechanism to cool indoor spaces, hence achieving thermal comfort in summer. Atrium ventilation, specifically, aims in ensuring the lowest possible indoor temperature in summer and to remove moisture and other air pollutants in winter with the possible energy consumption. These considerations determine the maximum and minimum ventilation capacity, respectively (Andersen, 2005).

According to Levermore (Levermore, 2002 cited in CIBSE Guide A, 2006) the heat transfer equation from surfaces and other sources is:

$$\Phi_v = NV(\vartheta_f - \vartheta_0)(1-e^{-x})/3 \qquad (4)$$

Where: Φ_v= heat transfer by ventilation (W)

N= the air change rate (h^{-1})

V= the room volume (m^3)

ϑ_f= the surface temperature of the building fabric's internal surfaces (^oC)

ϑ_0= the outdoor air temperature (^oC)

x=4.8A/(NV/3).

According to Approved Document F (Office of the Debuty Prime Minister, 2006) two types of ventilation can be provided:

- Infiltration: the uncontrollable air exchange between the inside and outside of a building through various air leakage paths in the building structure
- Purpose-provided ventilation: the controllable air exchange between the inside and outside of a building through various natural and/or mechanical devices.

The areas and resistances of the various apertures of a building, but also the pressure difference between the flow path's ends determine the air flow rates through the certain building. CIBSE (CIBSE Guide A, 2006) suggests that this pressure difference can be created by the following mechanisms:

- Wind
- Air density differences caused by internal-external temperature differences
- Pressure differences created by mechanical ventilation fans
- A combination of the three above mechanisms.

The ventilators that serve natural ventilation must be able to provide variable ventilation rates for different ventilation modes like for example trickle ventilators for winter mode and windows for summer mode.

3.5 Wind Driven Ventilation

In the windward sides of a building the surface pressure is high so air is driven inside the building by wind through openings and gaps. This air finally exits the building from the leeward side of the building where the pressure is lower through apertures or gaps after crossing the through the interior of the building, see figure 8. Higher wind speeds give higher infiltration and natural ventilation rates.

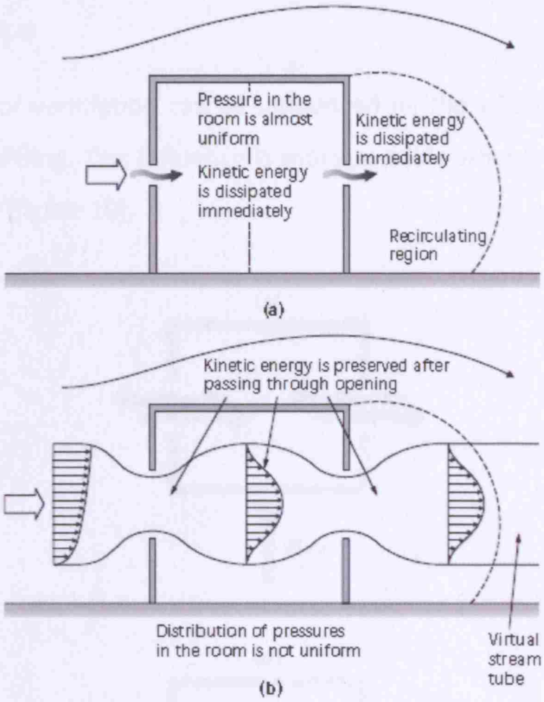

Figure 8. Flow configurations (a) through small openings, (b) through large openings [Kato, 2004 cited in CIBSE Guide A p.4-5)

3.5.1 Cross Ventilation

Cross ventilation is achieved when ventilation openings are provided on both sides of the ventilated space and basically relies on wind driving forces. As the air flows across the occupied space it picks up heat and pollutants and the deeper it moves into the space the less effective the ventilation is. The rule of thumb for effective ventilation limiting space depth is five times the floor-to-ceiling height. This approach is better applied to narrow plan buildings with the additional benefit of enhanced natural lighting opportunities.

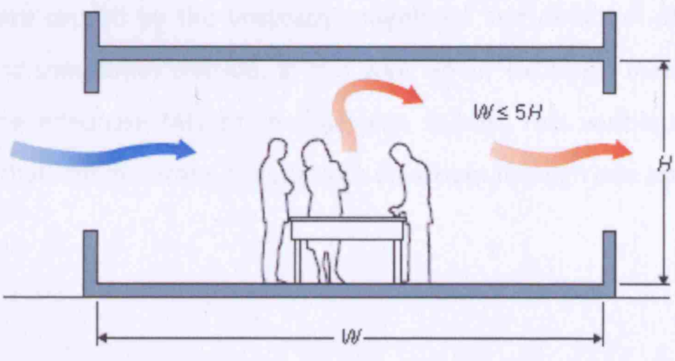

Figure 9. Cross Ventilation (CIBSE AM10, 2005 p. 16)

3.6 Wind Turbulence

The rate of infiltration or ventilation can be influenced by the wind's constantly fluctuating pressure field over a building. This influence is more sensible when average wind speed and stack effect are minimal (figure 10).

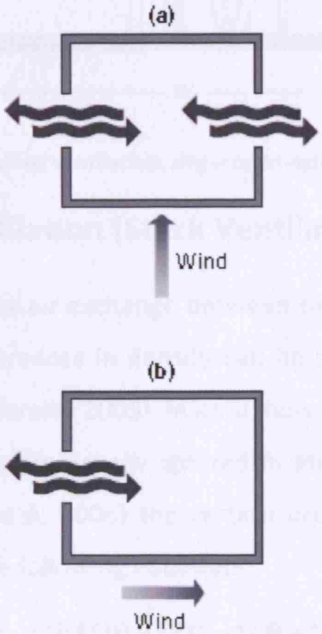

Figure 10. Effect of turbulent fluctuations of wind; (a) openings on opposite sides of enclosure, (b) openings on one side only (CIBSE Guide A p. 4-10)

3.6.1 Single-Sided Ventilation

Wind turbulence is important in achieving the required ventilation rates in cases where a space is ventilated through one opening alone. This opening will experience a rapidly fluctuating pressure caused by the unsteady magnitude and direction of wind, sometimes directed inside and sometimes outside. In this way, an air exchange mechanism is created, enough to provide adequate IAQ to shallow plan rooms. This ventilation mode is often applied to rooms that communicate directly with an atrium through one opening.

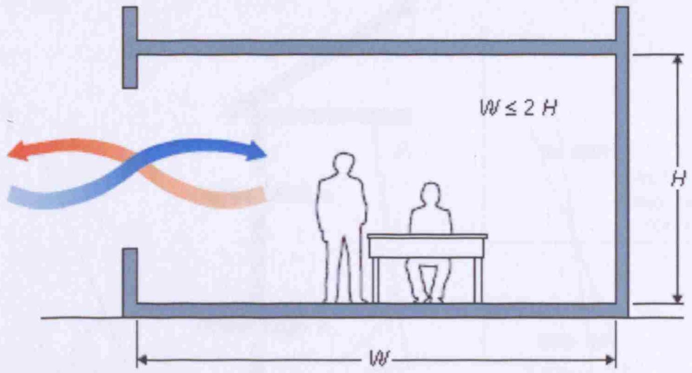

Figure 11. Single sided ventilation, single opening(CIBSE AM10 p. 15)

3.7 Buoyancy Driven Ventilation (Stack Ventilation)

Buoyancy driven ventilation is the air exchange between two or more zones caused by their air density differential. The differences in density can be due to different temperatures or different moisture contents (Andersen, 2005). In atria, however, the temperature differences rule so the moisture differences are usually ignored in atria thermal performance studies. According to CIBSE (CIBSE Guide A, 2006) the vertical pressure gradient created by these density differences is given by the following equation:

$$\Delta p = -\rho_o g 273(z_2 - z_1)[(1/(\theta_0 + 273)) - (1/(\theta_1 + 273))] \quad (5)$$

Where: Δp= the pressure difference (Pa)

ρ_o= 1.29 kg/m^3, the density of air at 0 °C

g= 9.81 kg/m^2, the acceleration due to gravity

z_1, z_2= the heights above ground level of openings 1 and 2

ϑ_0= the external temperature (°C)

ϑ_1= the internal temperature (°C)

The stack effect between any inter-connected vertically positioned openings is illustrated in Figure 12, while a quantitative expression of the stack effect is given in Table 1.

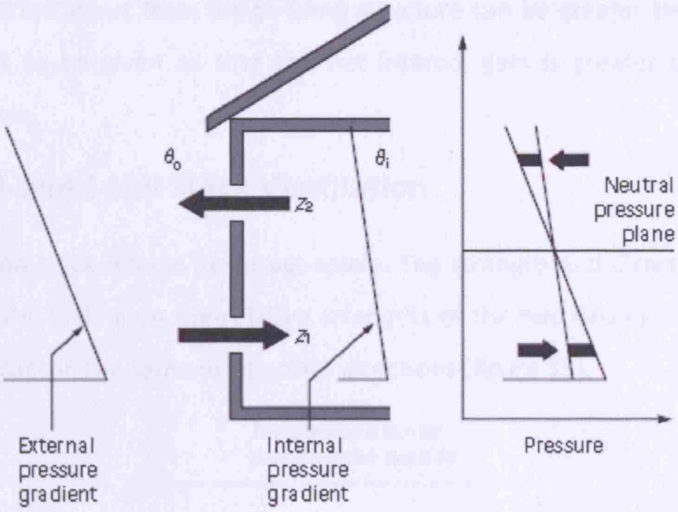

Figure 12. Stack effect (CIBSE Guide A p. 4-10)

Table 1. Pressure differences due to stack effect (CIBSE Guide A p. 4-10)

Temperature difference, $(\theta_i-\theta_o)$/K	Pressure difference (/Pa) for stated vertical height difference (/m)				
	5	10	20	50	100
-10	2.2	4.3	8.6	22	43
0	0	0	0	0	0
10	-2.2	-4.3	-8.6	-22	-43
20	-4.3	-8.6	-17	-43	-86

Note: minus sign indicates reduction in pressure with height, i.e. Flow upwards within the building

As observed from Table 1, when the internal temperature is greater than the one outside, $\theta_i-\theta_o>0$, the air enters the building from the lower opening and exits from the higher opening. In the case of $\theta_i-\theta_o>0$ the air flow is reversed. For $\theta_i=\theta_o$ there is no pressure difference to drive the air flow.

During summer, the external and internal temperatures are similar so there is a great chance that the stack will fail to perform as expected. Therefore, a heat gain source inside the ventilated space is found necessary to limit chances of air flow reversal. Such sources can be structural elements that absorb solar gain or other equipment that release considerable amounts of heat. However, care has to be taken that these heat gain sources do not influence the thermal comfort conditions of the occupied zones. If found necessary, on hot still days ventilation could be assisted by extract fans installed on the stack outlets.

In winter, conduction losses from the building structure can be greater than other heat gain sources. Care has to be given so that the net internal gain is greater than the heat lost through conduction.

3.8 Combined Wind and Stack Ventilation

In reality, wind and stack effects never act solely. The strength and directions of ventilation air flow will vary depending on the relative strengths of the two driving forces and whether they are acting locally in the same or opposite directions (figure 13).

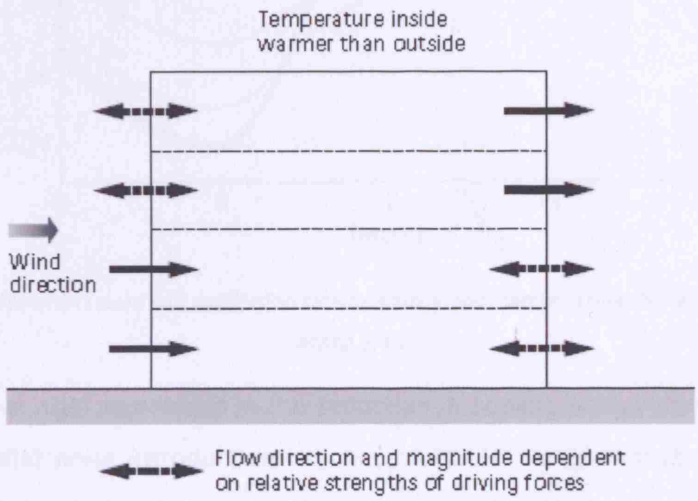

Figure 13. Combined wind and temperature driven airflow through a building (CIBSE Guide A p. 4-5)

3.9 Night Ventilation

Night ventilation provides great opportunities for ventilation cooling because it is applied at times when external temperatures are usually lower than internal temperatures. The large temperature difference between the inside and outside of a building enhance the cooling capacity of introduced air but also the stack driven flowrates.

Benefits from night ventilation are greatest when it is employed on heavyweight constructions. Heavyweight constructions have increased thermal capacity hence enhanced environmental admittance, and the amount of heat the structure can absorb per degree rise in mean radiant temperature is high. Thereby, such constructions manage to stabilize internal temperatures and reduce their peak value. During the evening, heat absorbed during the day is released and through night ventilation the building structure manages to cool down before the building is occupied. This lowering in the mean radiant temperature of the building enhances thermal comfort perception during the next day, when the ambient air temperature is high (figure 14).

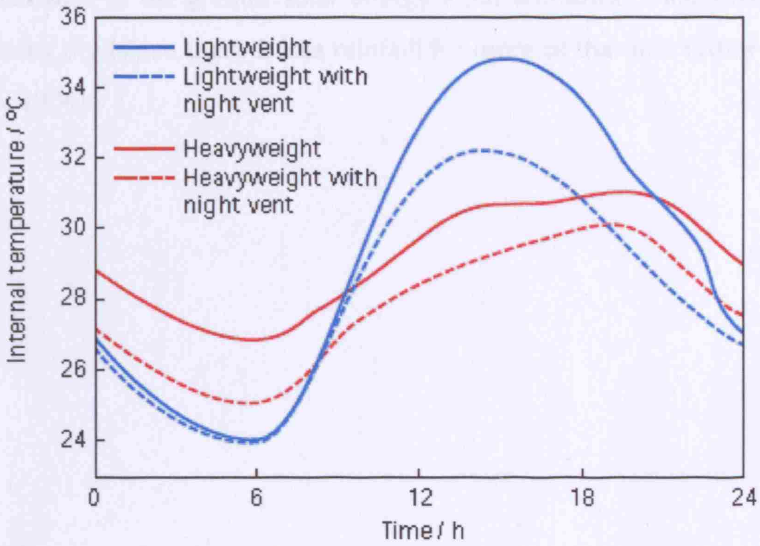

Figure 14. Effect of thermal mass and ventilation rate on peak indoor temperature (Baker n.d. cited in CIBSE AM10 p. 6)

Another benefit of night ventilation is the reduction in cooling energy demands during the day. Also, potential noise introduction or uncomfortable draughts that limit the cooling capacity of ventilation during the day stop being an issue when the building is unoccupied.

3.10 Urban Heat Island

Urban heat island is a phenomenon observed in large cities and involves the large air temperature difference between rural and urban areas. According to CIBSE (CIBSE Guide A, 2006) urban areas face larger temperatures than rural areas mainly because they have:

- Greater heat capacity
- More effective absorption of solar radiation in 'street gorges' and less effective long-wave radiative cooling
- Reduced wind speeds
- Less vegetation
- Anthropogenic heat flux

The maximum heat island recorded for London was 8 ^{0}K while the mean annual heat island for London is 2 ^{0}K. The heat island effect is more intense during the evening because of the heat storage effects of the urban fabric and the reduced radiative cooling and air speed compared to rural areas. The intensity of urban heat island is also greater in the summer than in the winter because of the greater solar energy input and lower wind speeds, and urban surfaces remaining dry (since there is less rainfall) for more of the time rather than in winter (CIBSE Guide A, 2006).

Chapter 4

4.0 Methodology & Aims

The case study building of this study is the Paul O'Gorman building which is part of the UCL campus. Paul O'Gorman atrium presents many features that make it an interesting case study for a report studying thermal comfort in naturally ventilated buildings and possible impacts of global warming on their performance. First of all, for reasons that concern building regulations the atrium space is considered as an unconditioned space relying only natural driving forces to provide it with adequate ventilation rates and cooling through ventilation. Secondly, occupants have no control over their thermal environment and have to accept the default ventilation mode. Thirdly, significant amounts of heat gain escaping from a plant room located in its lowest level help maintain internal temperatures higher than external for longer thus delaying the reversal of the stack. Still, these gains result to increased temperatures in the café located on the ground floor in immediate connection to the atrium basement where the plant room is located. During heating season these gains form the only opportunity for heating in the café area and help make temperatures in the café area more bearable. During cooling season though overheating risk is increased due to these gains and the cooling capacity of natural ventilation, the only possible cooling mode for the space is often not adequate to remove them.

The basic aim of this study is to analyze and assess the thermal performance of this complex case study atrium and the effect it has on the thermal comfort of occupants but also possible impacts of global warming on its performance. Both, field and simulation measurements were taken to help us draw more robust conclusions.

In the beginning of this study, an overview on thermal comfort issues and natural ventilation modes applicable in free-running buildings was made. Also an overview on atria and energy saving opportunities through natural ventilation was made. Before, reaching the data analysis point a thorough description of the case-study was done. All this information was provided to help the reader understand the techniques that would follow, studying all the issues mentioned above for the certain building.

In order to estimate the actual overheating risk of the café area but also to obtain an overall impression of the atrium's environmental performance, data loggers measuring Temperature and Relative Humidity (RH%) in 10 minute intervals, were placed in key areas of the Paul

O'Gorman main circulation area and atrium space. These results were also critical in confirming the reliability of our simulation results.

A calculation of the building's annual data concerning the atrium's environmental performance was conducted through a dynamic simulation in TAS. From this data a numerical assessment of the annual overheating risk was established. As the Design Summer Year (CIBSE DSY) was used for the simulations, the performance of the building under extreme conditions was determined and possible global warming effect could be assessed. Furthermore, it was possible to evaluate the thermal stratification in the atrium and its effect on the surrounding offices' thermal environment. The effect of air flow and night ventialtion on internal temperatures and thus on thermal comfort was also evaluated. More detail was given to the study of the hottest week of the DSY as it was considered rational that if the building performs nicely during hot spills, its performance is more likely to be satisfying during normal conditions as well.

A second simulation was run excluding heat gains from the basement plant room and where found necessary the results for this scenario were compared to the results of the running plant room scenario to help evaluate the plant room's effet on the atrium environement.

A third simulation including the raised protection border around the cafe space was also run to invesigate possible impacts on cafe temperatures.

Finally, field and simulation measurements were compared and conclusions were drawn on the atrium's thermal performance but also the impact of the natural ventilation strategy and the plant room's existence on occupant comfort.

Chapter 5

5.0 Case Study - Paul O'Gorman Building Atrium Space

5.1 Location's Climate

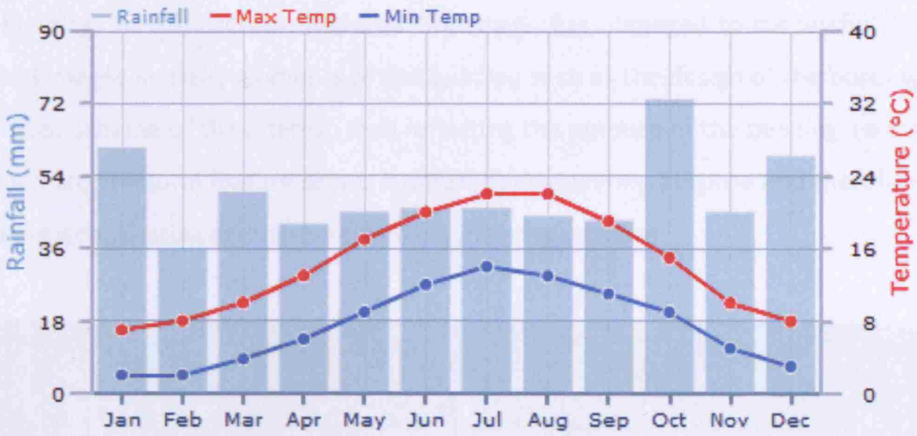

Figure 15. Monthly rainfall and temperature data for London, UK (Globe Media Ltd, 2008)

London has a temperate climate, with modest daily high temperatures during summer (apart from the odd heat wave) and winter lows that rarely fall below freezing. Rainfall is relatively regular, but most often in the form of drizzle, occurring throughout the year. Snow occasionally occurs in winter but rarely settles more than a few millimeters deep (Globe Media Ltd, 2008).

5.2.1 Urban Heat Island Effect

The Paul O'Gorman building is located approximately 500 m away from the British Museum which is the eye of the heat island. Therefore, the effects of urban heat island, especially during summer and hot still nights can decrease the effectiveness of night ventilation for the Institute of Cancer thus making the application of a natural ventilation strategy an engineering challenge.

5.2 Background of Surrounding to the Atrium Buildings

5.2.1 Paul O'Gorman building-UCL Cancer Institute

The Paul O'Gorman building was named after a boy who died of leukaemia at the age of 14 and whose last will was that his parents would help children with the same illness. It achieved practical completion in April 2007 and was officially opened in September 2007 (UCL, 2008). It consists of laboratories on seven floors and has a housing capacity of 350 staff for the 4500 m^2 laboratory and offices floor area.

Located in the UCL campus, in central London, the Cancer Institute forms one of the most unique buildings of the campus. Nicholas Grimshaw, has managed to successfully integrate biomedical images in many elements of the building such as the design of the building facade and the color scheme of the interior, thus reflecting the purpose of the building (e-architects, 2008). Each architectural feature serves a different engineering purpose and therefore makes the building a captivating architectural and engineering creation.

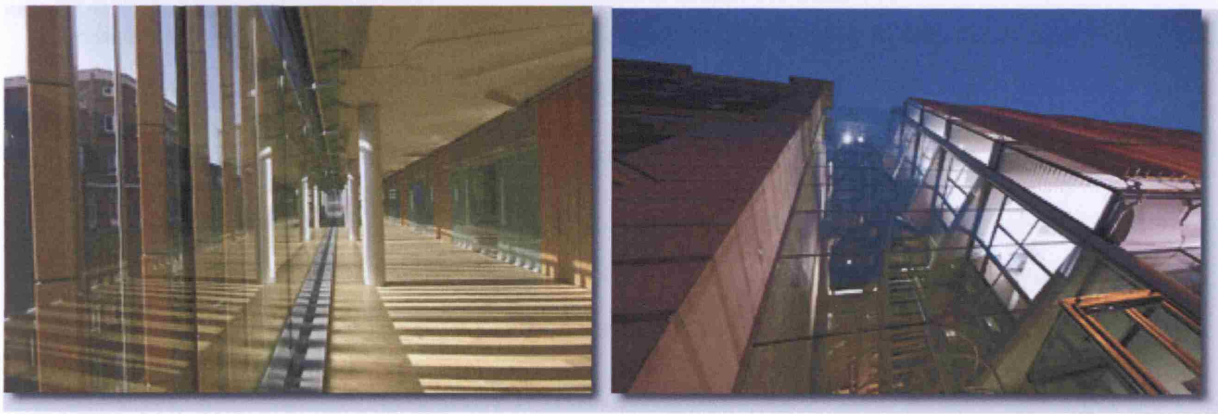

Figure 16. Paul O'Gorman building (UCL, 2008)

5.2.1.1 Construction Elements

The front facade faces Huntley Street and consists of a 1.5 cm single green laminated glazing. A series of terracotta louvers prevent 50% of direct sunlight from entering the office area and give the building a dynamic touch. Internally, the walls and ceiling consist mostly of exposed reinforced concrete while the floor is consist of ceramic tiles (UCL, 2008).

The laboratory and office spaces have timber floors while the walls are made either out of glass or timber acoustic panels. The ceiling is consist of exposed concrete soffits. The facade that communicates with the atrium is again glazed.

5.2.1.2 HVAC Systems

In a personal conversation, Graham Bonnett, the M&E engineer of the building, admitted that in order for the amount of glazing used for the building to be permitted from building regulations, the circulation spaces communicating directly with the main staircase as well as the atrium space had to be treated as external spaces. Therefore, these spaces are left unconditioned in terms of mechanical heating, cooling and ventilation. The main staircase area is heated passively by solar and internal gains but it is also cooled passively though radiative cooling from thermal mass and through ventilation. The plant room provides heating to the atrium space during winter but also contributes to its overheating during winter. Huntley Street is not a busy road therefore the air taken in for ventilation means is considered to be of good quality for city center standards. Apart from the circulation areas and atrium, the rest of the building is fully air-conditioned.

5.2.2 Rockefeller & Medical Sciences Building

The Medical School building was renamed to Rockefeller building in 1980 after re-uniting with UCL. It was first built in 1825 and has been through many schemes of improvement since then. Today it forms a new issue desk and offices and takes part in UCL's computerized library management system (UCL, 2007)

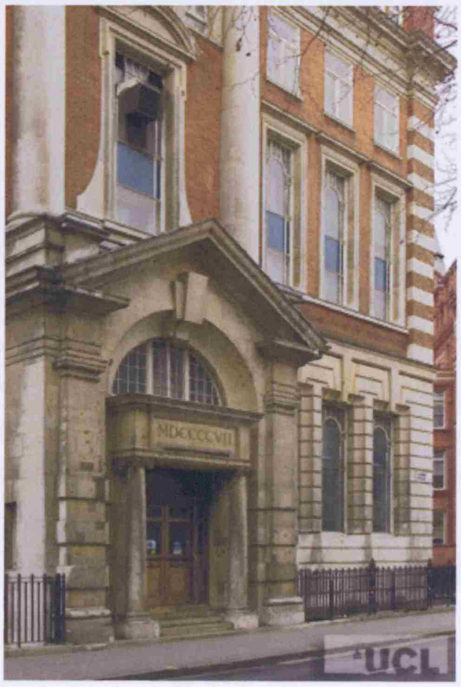

Figure 17. Photograph of the Medical School Building, which was later renamed the Rockefeller Building (UCL, 2007)

5.2.2.1 Construction Elements

External walls are consist of double brick layers, insulation and cavity. Internally, the walls and ceiling consist mostly of concrete while the floor is consist of plastic tiles. All U-values of the constructions elements comply with building regulations for existing buildings as it has been recently refurbished.

5.2.2.2 HVAC Systems

All offices and rooms in the building are air-conditioned. However, occupants often rely on single sided ventilation through one opening for achieving thermal comfort and good IAQ, as thermal conditions in the atrium space regularly allow for it.

5.3 Description of Atrium Space

The case study atrium is a core atrium and it is located between the UCL Institute of Cancer, the Rockefeller and Medical Sciences building. It hosts a cafe that serves occupants from these buildings.

Figure 18. Atrium space view (Photo by the author)

What makes this space unique and worth of studying is the existence of a plant room in the basement area which covers the primary heating demands of many of UCL campus buildings. Waste heat escapes from the plant room into the atrium basement area and as studied later on has many important and interesting effects on the environmental conditions in the atrium space. Air can be provided in the atrium space through an inlet located in the atrium basement and through the café entrance both communicating with the Paul O'Gorman main staircase area. The main inlet that introduces air from the outside is located on the basement floor façade of the Paul O'Gorman building. This main inlet, as well as the outlets in the atrium top are automatically controlled according to the temperature in the cafe seating area.

The atrium roof is consist of two ETFE (Ethylene Tetra Flouro Ethylene) foil layers. These thin films are supported in an aluminium perimeter extrusion supported on the building frame. (Architen Landrell Associates Limited, n.d.).

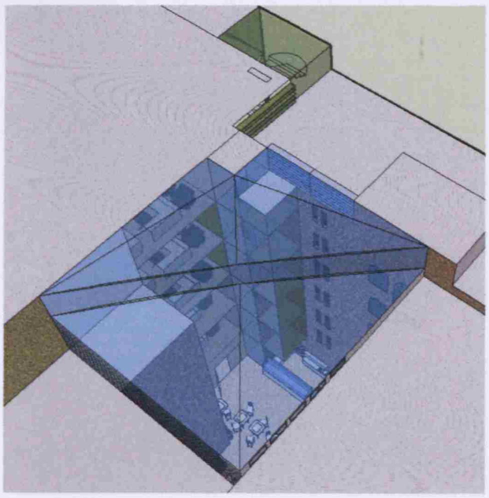

Figure 19. Aspect of atrium roof

ETFE foil has a light transparency of approximately 94-97% of total light, is unaffected by UV light, atmospheric pollution and other forms of environmental weathering. The Cushions are inflated by a small inflation unit to approximately 200 Pa which gives the foil a structural stability and gives the roof high insulation properties (Architen Landrell Associates Limited, n.d.).

5.4 Ventilation Strategy of Atrium Space

The primary air flow routes serving the ventilation strategy are illustrated in figure 20.

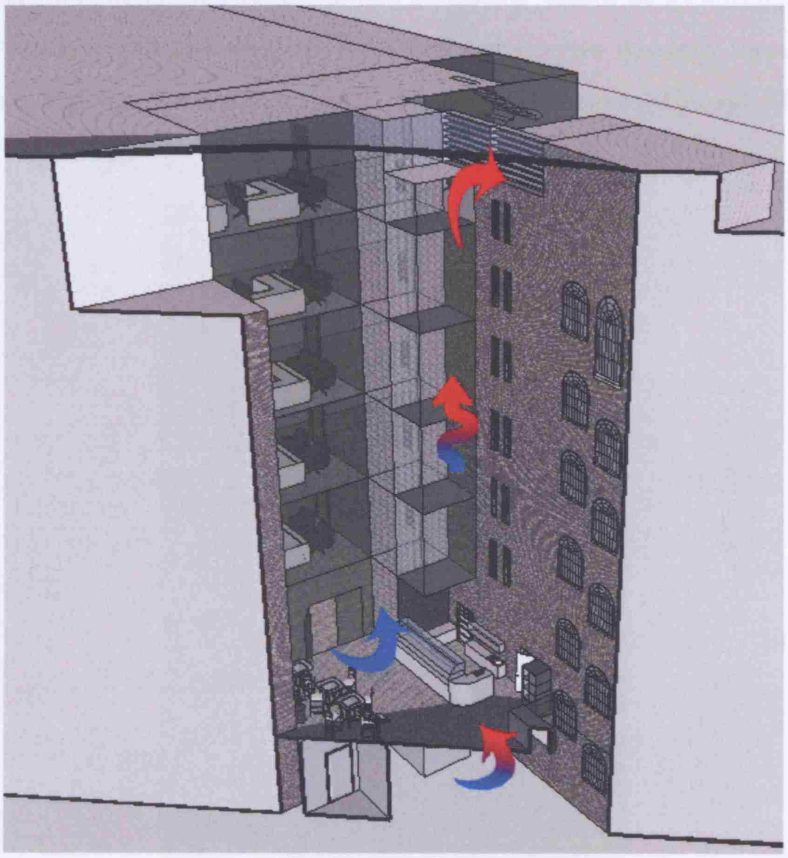

Figure 20. Primary air flow routes for atrium space ventilation

5.4.1 Summer Operation

The main ventilation inlet is located in the basement floor facade that faces Huntley Street. This air reaches the atrium space through a basement inlet that connects the atrium basement with the basement of the Paul O'Gorman building and is open all day round. As cool air flows by the plant room it picks up heat and becomes less dense. This air rises upwards as a result of its small density and is displaced by new cooler air.

Between 08:00 A.M. to 18:00 P.M., on weekdays, a second air flow is allowed into the atrium space through the cafe entrance driven there by pressure differences between internal and external but also between atrium space and Paul O'Gorman main circulation area. This air flow picks up heat from the occupants and equipment of the cafe, but also from the plant room. As the air is heated up it rises upwards by buoyancy means and is purged out through the high level outlet.

Some of the air that enters the Paul O'Gorman building is heated up by internal and/or solar gains before reaching the atrium space so it is forced to rise upwards through the main staircase area. A high level outlet is located at the top of the staircase through which warm air is purged out (figure 21).

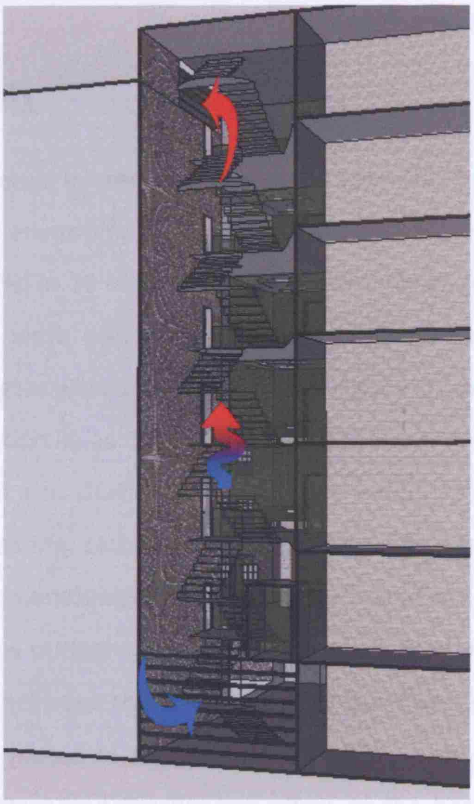

Figure 21.Primary air flow routes for main staircase ventilation

5.4.2 Night Operation

The increased cooling capacity of the evening external temperatures is exploited to precool the fabric of the building and remove remaining heat from the plant room's day operation therefore precooling the building and preparing it for occupation the next day. Cool air either enters the atrium space through the basement inlet and is purged out through the top atrium outlets, or it rises up the main staircase area where it is purged out by the high level outlet.

5.4.3 Winter Operation

During winter the external inlet and outlets are kept closed to limit heat losses and uncomfortable draughts. Basic infiltration rates are provided from the transient opening of the Paul O' Gorman main entrance and through background ventilation. However, in cases of overheating, during mid-season, the main inlets and outlets are scheduled to open, this time however at higher temperatures, to avoid uncomfortable draughts caused by the cold external air.

5.5 Monitoring Results

In order to estimate the actual overheating risk of the café area but also to obtain an overall impression of the atrium's environmental performance, data loggers measuring Temperature and Relative Humidity (RH%) in 10 minute intervals, were placed in various zones of the case study area. These results were also critical in confirming the reliability of our simulation results. 4 pairs of data loggers were placed inside and right outside offices of different height level and different orientation so as to record the effect of the atrium thermal conditions on the surrounding offices but also stratification inside the atrium space. Furthermore, 3 loggers were placed in the cafe seating, cashiers and reception area, respectively, at 1 m height, to study the thermal comfort conditions in these unconditioned occupied areas. Also, a logger was placed internally on the outlets and another one was placed externally on the inlet vents so as to allow comparison between the air entering the building and that leaving the building. Finally, a data logger was placed in the basement area so as to record the size of internal gains released from the plant and the cooling effect of the basement inlet, to this space during the evening.

It was considered wiser to compare internal monitored data with the data of the air entering the building rather than from the file of a weather forecasting service, thus the information from the data logger placed on the external side of the inlet was used to represent the external conditions.

The data loggers were set into position between 12:00 am and 13:00 pm of June 10th and were removed between 11:00 and 12:00 am of July 9th. During this time the data loggers managed to capture data for a wide range of weather conditions. Specifically, they monitored the hottest day of the year but also cold and very humid days.

A synopsis of the external conditions and the conditions in the main occupied areas are found in table 2, for all occupied hours of the monitoring time. The thermal comfort zone we set for the free-running occupied spaces of the building is 18 to 25 °C for dry bulb temperature and 30 to 70% for relative humidity, while an overheating risk zone between 25-28 °C was also set. For all seasons we assume activity, seated-relaxed of 1.0 Met and clothing 1.0 clo while for cooling season we assume the same activity but clo value of 0.7.

Table 2. Synopsis of internal and external conditions for all monitored occupied hours

	All Monitored Occupied Hours									
Zone	$T_{average}$ (°C)	T_{max} (°C)	T_{min} (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C	$RH_{average}$ (%)	RH_{max} (%)	RH_{min} (%)
External	20.1	29.1	14.5	25.6%	69.4%	5.0%	1.6%	53.2	90.6	32.4
Reception	20.8	25.2	17.8	0.2%	99.6%	0.2%	0.0%	48.1	70.7	33.2
Cafe Seating	25.5	29.5	22.9	0.0%	36.7%	61.0%	3.3%	38.2	51.7	28.2
Cashiers'	25.7	29.6	23.1	0.0%	27.7%	72.3%	3.9%	39.5	53.3	30.0

As established from table 2 and figure 23, air that enters the building is rather cool and humid but as it picks up heat from internal gains it becomes warmer and thus less humid when it reaches the atrium space. Even though the cashiers area presents slightly higher than the cafe seating area temperatures it also presents slightly higher Relative Humidity values because of the latent heat gains from the equipment there. The reception area presents thermal conditions that are in between those for the external and café area. All these observations were taken into consideration in the modeling of the building.

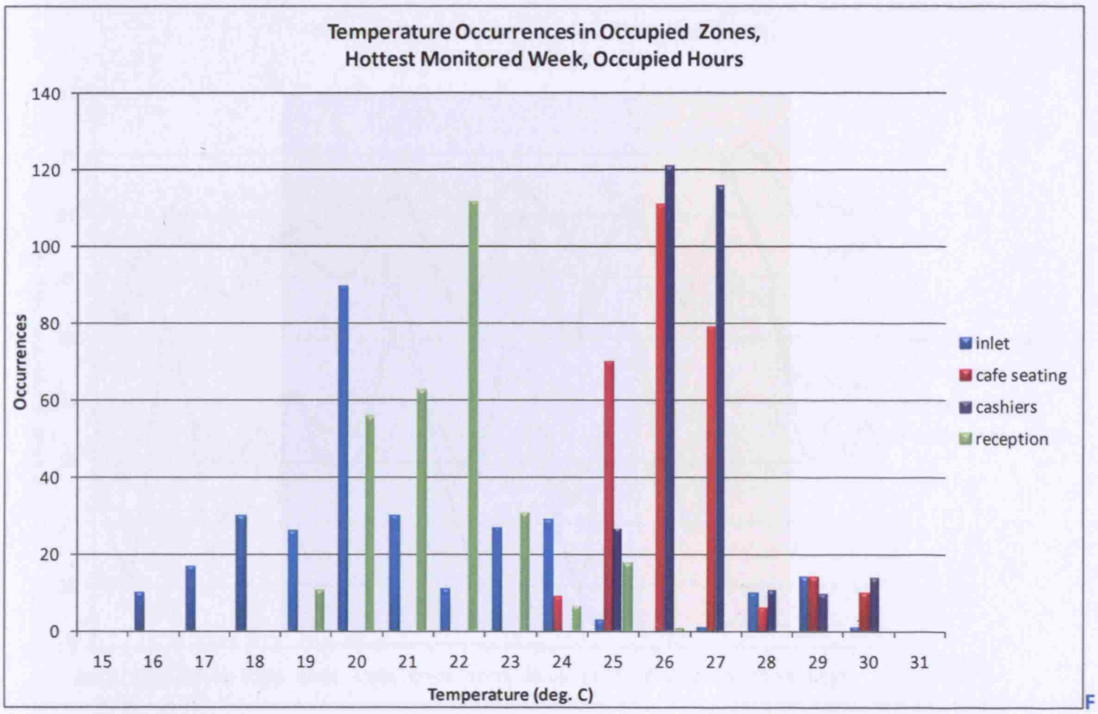

Figure 22. Temperature occurrences for the main occupied areas on occupied hours of the hottest monitored week

The data loggers helped us understand better how the internal conditions are affected by occupancy and internal gains schedules and thus improve our simulation model (figure 23).

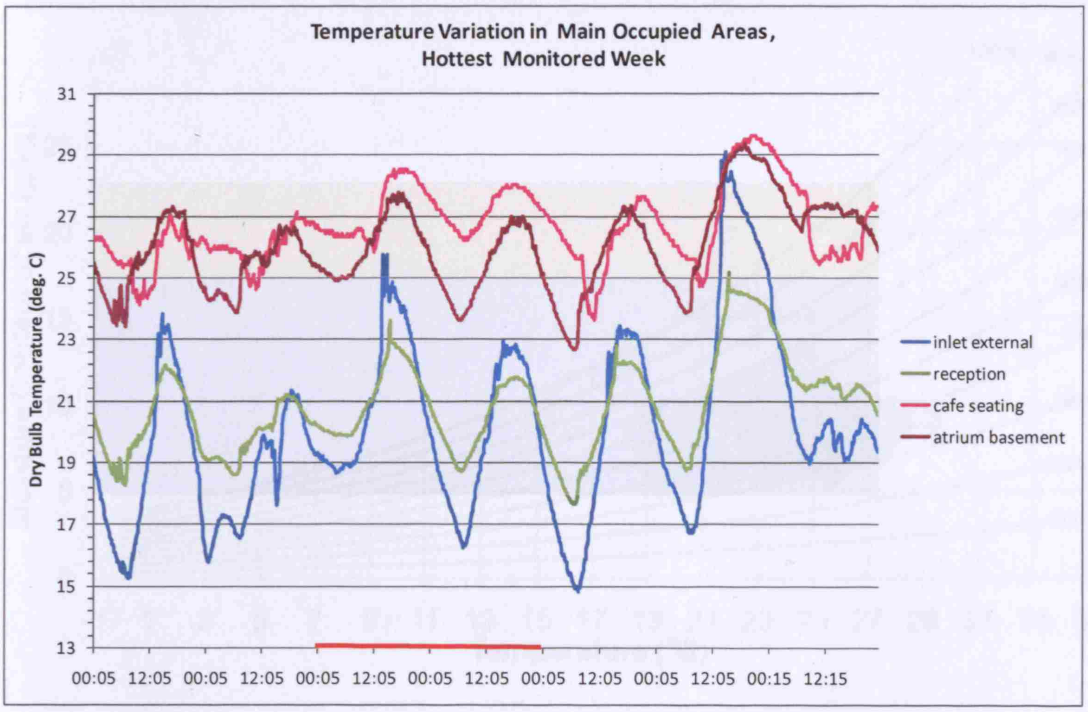

Figure 23. Diurnal Temperature Variation for main occupied areas during the hottest monitored week – red line indicates the weekend

A sharp increase of 1 to 1.8 °C was recorded for the atrium basement every weekday morning at 07:00 am giving away the plant room's operation starting time. Later on, at around 8:15 am, a sharp decrease of 0.7 to 2.0 °C was monitored in the cafe seating area as a result of the opening of the cafe entrance.

In general, as observed from figure 23, for the first occupied hours the café seating area presents temperatures lower than the corresponding atrium basement temperatures. After mid-day though, when internal gains pile-up in the café seating area the opposite is observed and it is not reversed again until the opening of the café entrance the next morning. During the evening the cafe seating area receives the warm buoyant air from the night ventilated basement and the lack of airflow through the shut cafe entrance do not allow for them to be removed adequately through night ventilation thus resulting to high temperatures in the café area. The lack of the cooling effect occurring from the opening of the cafe entrance is also profound during weekends for which the seating area remains hotter than the basement the whole time. This could also be a result of the lack of heat gains from the inoperative plant room which would otherwise enhance the stack effect in the atrium space (see TAS chapter).

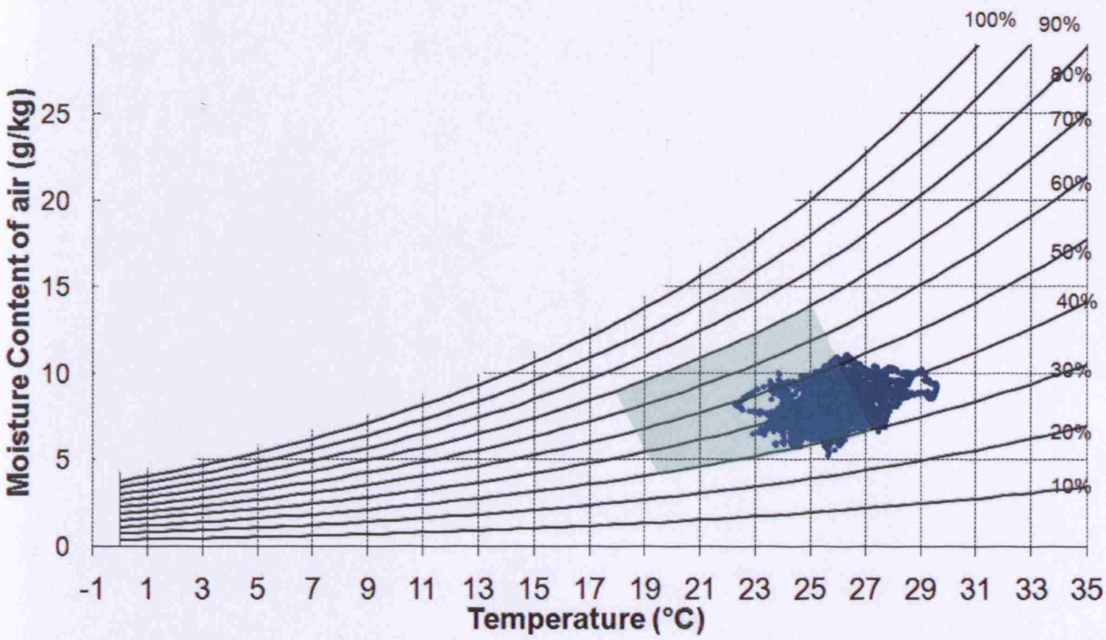

Figure 24. Psychrometric chart for cafe seating area for all monitored occupied hours

Overall, as concluded from the psychrometric chart of the cafe seating area, the occupants experience discomfort due to overheating very often. The role of the plant room in this result is studied further below.

Chapter 6

6.0 TAS Software Modeling and Results

6.1 TAS Software

TAS is a thermal simulation software package through which the dynamic thermal performance of buildings and their systems can be simulated. It is comprised of TAS Building Designer, a module that performs dynamic building simulation with integrated natural and forced airflow, and TAS Ambiens, a 2D CFD package which produces a cross section of micro climate variation in a space (EDSL, 2008). In this study only TAS Building Designer to provide us with annual data on the building performance in an extreme year.

6.1.1 3D Model Design

As shown in figure 25 the building model designed in TAS 3D Modeler was kept quite simple and detail was only given to elements that affect the performance of the stack such as total height of the stack and openings' positions and sizes but also construction elements. Not much detail was given to the design of the shaded front facade or the offices that are not adjacent to the naturally ventilated spaces as they are air-conditioned and independent so their effect to the thermal performance is considered to be minimal. Note that the building opposite the main facade was also included in the simulation, as a surrounding building but does not appear in figure 25.

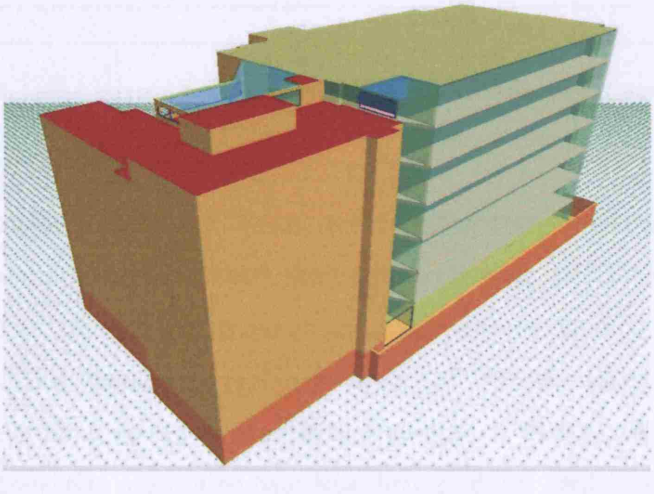

Figure 25. TAS Manager 3D Model Design

6.1.2 Weather File

In order to determine the overheating risk of the unconditioned areas of the building the simulation was carried out with the use CIBSE London Design Summer Year (London DSY) weather file. This weather file provides weather conditions for a warmer than average year. Therefore, the performance of the building under extreme conditions and possible global warming effect can be assessed.

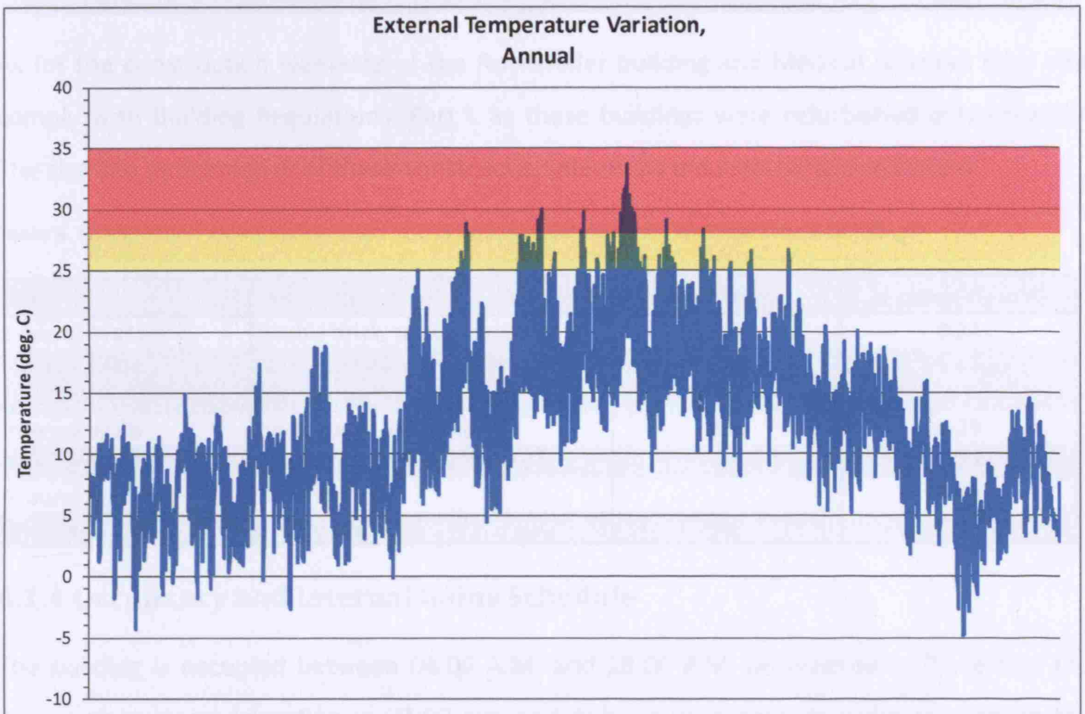

Figure 26. Annual external temperature variation for CIBSE London DSY weather file

6.1.3 Building Elements

Paul O'Gorman is a new building and the construction elements comply with Part L2A of the 2006 Building Regulations (Office of the Deputy Prime Minister, 2006). The U-values for the external walls, roof but also for the glazed areas comply with the limiting U-values from Part L2A of the 2006 Building Regulations (appendix table B1). The internal walls however do not comply with these limiting values as their actual purpose is to take advantage of thermal mass properties rather than preventing heat loss through them. Table 3 summarizes the size and performance of the construction elements.

Table 3. Construction elements assigned in TAS Building Simulator for Paul O'Gorman building

Element	Description	Width (mm)	U-value (W/m^2K)
External Walls	double brick, cavity, insulation	500	0.23
Glazed Walls	double glazing, internal blind	32	1.79
Floors-ceiling	concrete ceiling, tiled floor	540	1.13
Internal Walls	Reinforced concrete	300	2.4
Roof	concrete roof, flat, insulation	530	0.22
Ground Floor	Ground floor		0.17
Atrium roof	single glazing	30	5.0
Front Facade	double glazing, external blind	24	1,37

As for the construction elements of the Rockefeller building and Medical Sciences they also comply with Building Regulations' Part L as these buildings were refurbished only recently. The size and performance of these construction elements are summarized in table 4.

Table 4. Construction elements assigned in TAS Building Simulator for Medical School buildings

Element	Description	Width (mm)	U-value (W/m^2K)
External Walls	double brick, cavity, insulation	500	0.23
Floors/Ceiling	concrete ceiling, insulation, plastic tiles	360	0.25
Internal Walls	brick, cavity, insulation	335	0.29
Roof	concrete roof, flat, insulation	405	0.23
Ground Floor	Ground floor		0.23
Windows	double glazing	24	1.8

6.1.4 Occupancy and Internal Gains Schedule

The building is occupied between 08:00 A.M. and 18:00 P.M. on weekdays. Therefore, the power plant starts operating at 07:00 am, and only on weekdays, in order to prepare the building for occupation in terms of heating and hot water supply. It also shuts at 18:00 pm. During heating season the gains released from the plant room are greater than those released during cooling season. This happens because during winter there is a need for space heating as well as for hot water.

6.1.5 Infiltration Rates

Advise for the infiltration rates was taken from CIBSE Guide A. 0,3 ACH were assigned for all rooms as advised for new or refurbished buildings. Yet, an extra 0,5 ACH was assigned to the reception area for occupied hours so as to simulate the transient opening of the Paul O'Gorman main entrance door, which due to the great pressure difference between internal and external allows a large amount of air inside when opened.

6.1.6 Aperture Schedules

All apertures simulated, apart from the cafe entrance, are automatically controlled. Their operation schedule is summarized in table 5.

Table 5. Aperture Schedules used in TAS Building Simulator

Aperture	Zone of reference	Day type schedule	Season schedule	Start opening	Fully open	Cut-off
Main Inlet	cafe seating	weekday, weekend	Heating period	24 C	24 C	¬
			Cooling period	20 C	222C	¬
Atrium Outlet	cafe seating	weekday, weekend	Heating period	24 C	24 C	¬
			Cooling period	20 C	22 C	¬
Main Staircase Outlet	reception	weekday, weekend	Cooling period	20 C	22 C	¬
Office Windows	adjacent zone	weekday	Annually	21 C	22 C	24 C
Cafe Entrance	cafe seating	weekday	Annually	8:00 AM	8:00 AM	18:00 PM

6.1.6.1 Summer Operation

During cooling season the apertures are used for ventilation but also for cooling through ventilation. Therefore, the temperature limits for which the apertures operate are lower than those for heating season. The higher internal and external temperatures allow for high ventilation rates that enhance the perception of cooling by reducing the dry resultant temperature (figure 2).

6.1.6.2 Winter Operation

In the heating period heat losses and uncomfortable draughts are prevented by keeping the atrium external inlets and outlets shut. Indoor Air Quality (IAQ) is achieved through background ventilation. Nevertheless, in order to deal with possible overheating during mid-season the inlets and outlets do operate but at a higher than in summer temperature limit to avoid uncomfortable draughts.

6.1.6.3 Operation of Atrium Office Apertures

The buffer zone effect the atrium space has for the atrium offices allows for the adjacent to the atrium office apertures to have the same aperture schedule throughout the year. The cafe entrance is manually controlled according to the cafe operational hours even though it plays a significant role in the ventilation strategy, as established later on.

6.1.7 Zoning

Three major zoning groups were assigned: the medical school offices, the atrium space and the Paul O'Gorman building main staircase area.

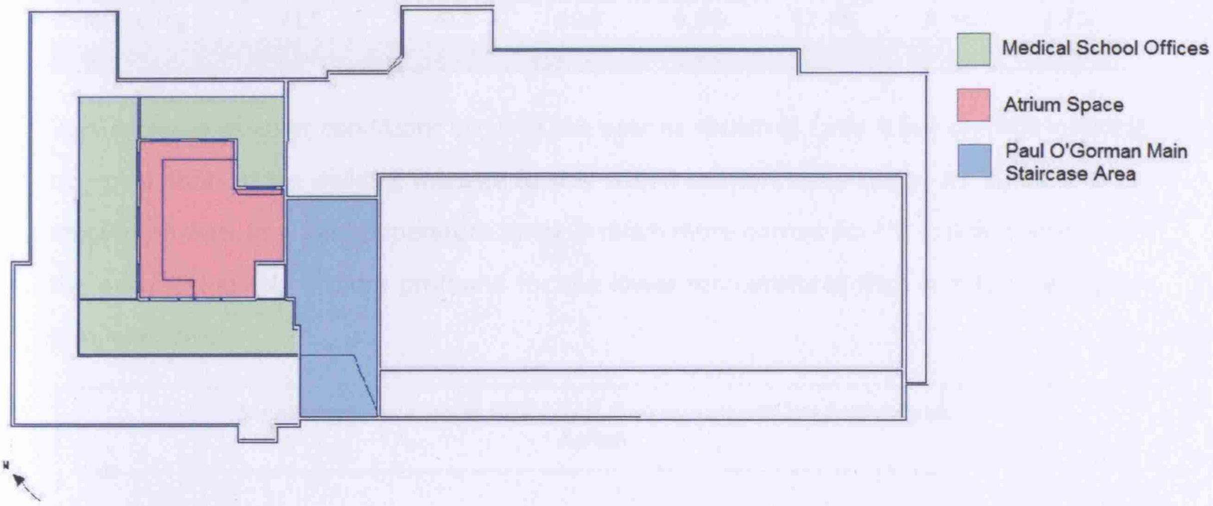

Figure 27. Zoning of simulation model

Some medical school offices have windows adjacent to the atrium space. Because the atrium space acts as a buffer zone between internal and external environment it will be interesting to see the variation in energy demand loads for different floors and orientation of offices.

The successful co existence of a habitable space –the cafe- with an area of significant heat disposal –the basement plant room- can be assessed through the study of the atrium zone.

However, the cafe area and plant room could have never co-existed if it wasn't for the fresh cool air intake from the basement and ground floor of the Paul O'Gorman main staircase area. The initiation point of the air flow path can be studied in this zone.

6.2 TAS Simulation Results

The results occurring from simulations show that the natural ventilation strategy of the building serves its purpose successfully for most of the year.

Table 6. Synopsis of annual internal and external conditions

	Annual, Occupied Hours						
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	13.9	31.1	-4.7	70.3%	22.0%	6.6%	1.5%
Reception	19.9	29.4	11.1	23.9%	69.7%	6.4&	0.6%
Cafe Seating	21.5	30.1	10.8	9.3%	82.4%	8.3%	1.3%
Cashiers'	21.5	30.2	10.6	9.8%	81.6%	8.6%	1.3%

Very extreme weather conditions occur in the year as shown in table 6 but the free-running occupied areas of the building manage to stay within comfort limits (18 to 25 °C) for a large amount of time. Internal temperature range is much more narrow for the inside than it is for the outside and this is more profound for the lower temperatures than it is for the higher temperatures.

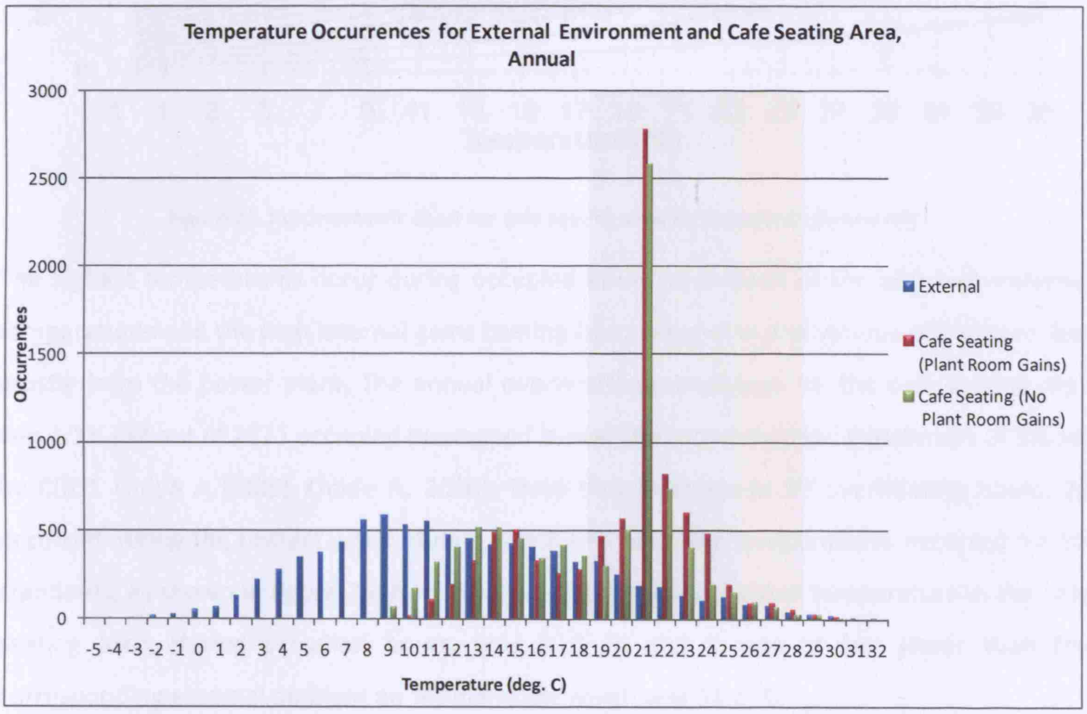

Figure 28. Annual external and cafe seating area temperature occurrences

Figure 28 gives an illustration of this observation for the most densely occupied area, the cafe seating area. As shown, the gains occurring from the basement plant room have a greater effect on winter temperatures than on summer temperatures, meaning that they increase comfort conditions for heating period by a large factor but contribute to overheating only by a small fraction. Similar figures for the other occupied areas of study –the reception and the cafe cashiers' space- are found in the appendix.

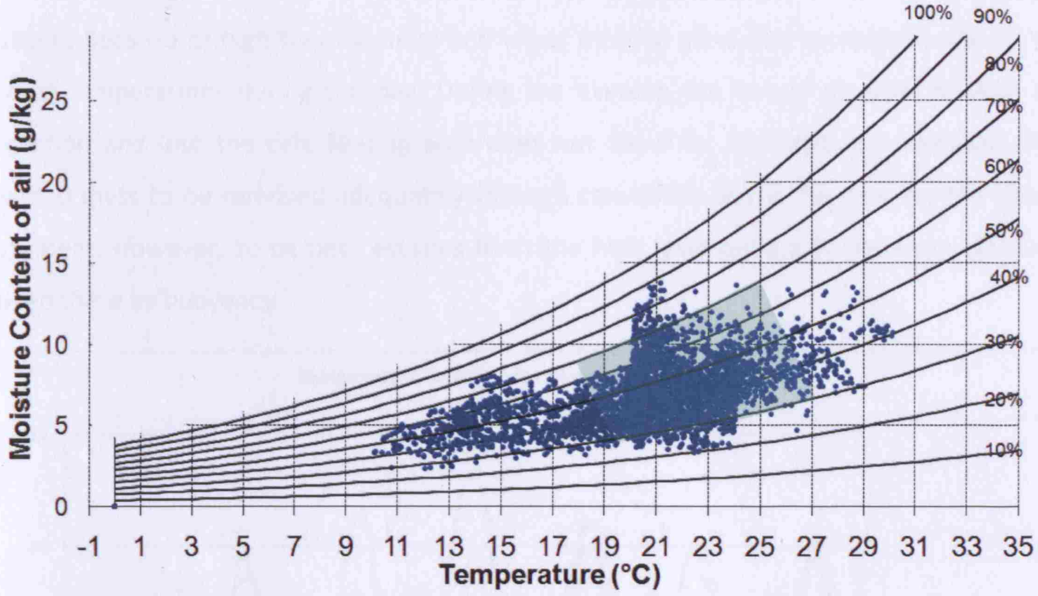

Figure 29. Psychrometric chart for cafe seating area for occupied hours yearly

The highest temperatures occur during occupied hours as a result of the also high external temperatures and the high internal gains coming from occupants and various equipment but mostly from the power plant. The annual overheating percentage for the cafe seating area was 1.3% (37 out of 2871 occupied hours) and is over the recommended benchmark of 1% set by CIBSE Guide A (CIBSE Guide A, 2006). Note that from these 37 overheating hours, 23 occurred during the hottest week, during which very extreme temperatures occurred for UK standards, as shown in figure 26. Nevertheless, the highest recorded temperature in the cafe seating area, during occupied hours, was 30,1 °C and it was in fact lower than the corresponding external ambient air temperature which was 31,1 °C.

6.2.1 Hottest Week

As observed in figure 30, the hottest week of the year (19th to 25th July) was extreme and it was the only week of the year for which external temperatures exceeded 30 °C. The hottest day of the year occurred on a weekend. For a more objective view we studied more thoroughly the third hottest day of the year during which the building was occupied (day 204). Results obtained for weekends are not objective as no heat gains occur from the plant room, occupants and other equipment and the cafe entrance that would otherwise provide an extra air flow path is shut.

As shown in figure 30 internal temperatures follow the external temperature variation pattern. Because of high thermal mass and lower internal gains, the reception presents the lowest temperatures during the day. During the evening the lack of air flow through the reception and into the cafe seating area does not allow for the heat now released from thermal mass to be removed adequately through convection like is the case for the atrium basement. However, some heat escapes from the high level outlets in the main staircase, driven there by buoyancy.

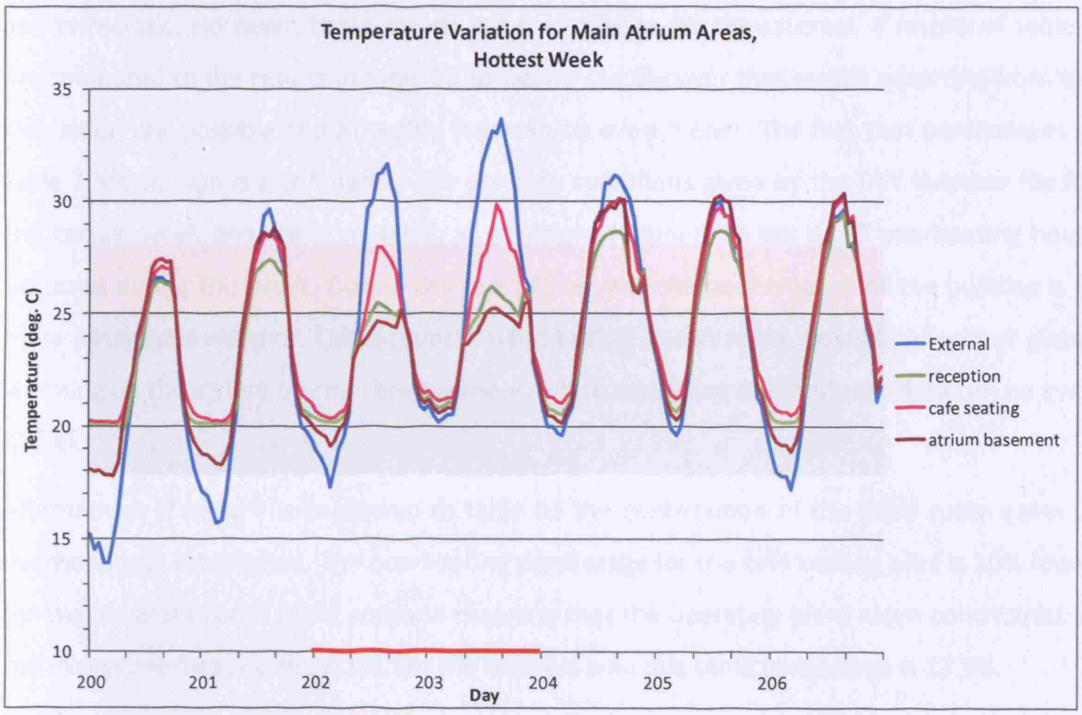

Figure 30. Diurnal temperature variation for main occupied areas for the hottest week (19th to 25th July) – red line indicates the weekend

For the hottest occupied day internal temperatures remained lower than external temperatures, even though overheating occurred for all the occupied areas. However, if compared to the following two days, day 205 and 206, someone would suggest that the reason for this is the fact that the previous to the hottest occupied day was a weekend during which the atrium basement had time to cool down adequately from the effect of the running plant room. This effect of the plant room on the diurnal variation for the main occupied areas on the hottest week is made more profound by comparing figure 30 to figure B3.

Table 7. Synopsis of internal and external conditions for the occupied hours of the hottest week

	Hottest Week, Occupied Hours						
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	26.6	31.1	18	0.0%	25.4%	76.4%	41.8%
Reception	26.1	29.4	19.8	0.0%	27.3%	72.7%	29.1%
Cafe Seating	26.9	30.1	20.6	0.0%	16.0%	84.0%	41.8%
Cashiers'	27	30.2	20.7	0.0%	16.0%	84.0%	41.8%

Table 7 summarizes internal and external conditions results for the occupied hours of the hottest week. At a first glance the internal percentages of overheating seem extremely high and unrealistic. However, these results are the same as for the external. If results of table 7 are compared to the results of table 13 someone can discover that results occurring from the simulation are possible and in reality they can be even higher. The fact that percentages in table 7 are so high is attributed to the extreme conditions given by the DSY weather file for the certain week and are acceptable; as mentioned earlier, 23 out of 37 overheating hours occurred during this week. During the rest of the year the performance of the building is in more acceptable margins. Consequently, what table 7 shows is the possible impact of global warming on the atrium thermal environment, which according to monitored data can be even higher.

Alternatively if table 7 is compared to table B3 the contribution of the plant room gains to overheating is established. The overheating percentage for the café seating area is 10% lower for the 'no plant room gains' scenario meaning that the operating plant room contributes to the excess overheating by 26.1%. For the cashiers area this same percentage is 17,5%.

6.2.1.1 Night Ventilation

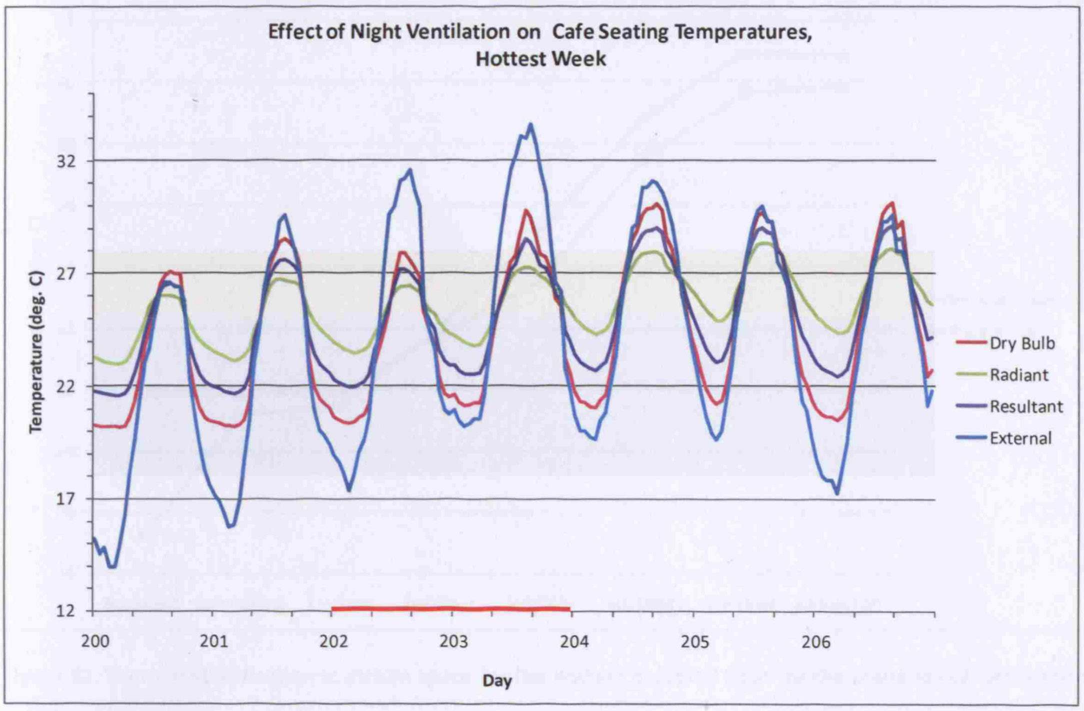

Figure 31. Effect of night ventilation on café seating temperatures for the hottest week- red line indicates the weekend

The occupancy schedule of the building but also its adjacency to a non-busy road encourage the application of night ventilation. Night ventilation effectively helps remove heat from the lower level atrium and lower the mean radiant temperature during the next day. Therefore, even though during the day the ambient temperature is rather high, occupant cooling perception is enhanced by radiative cooling from the construction.

6.2.1.2 Thermal Stratification

The thermal stratification inside the atrium for the hottest hour of the hottest occupied day of the year is illustrated in the following figure.

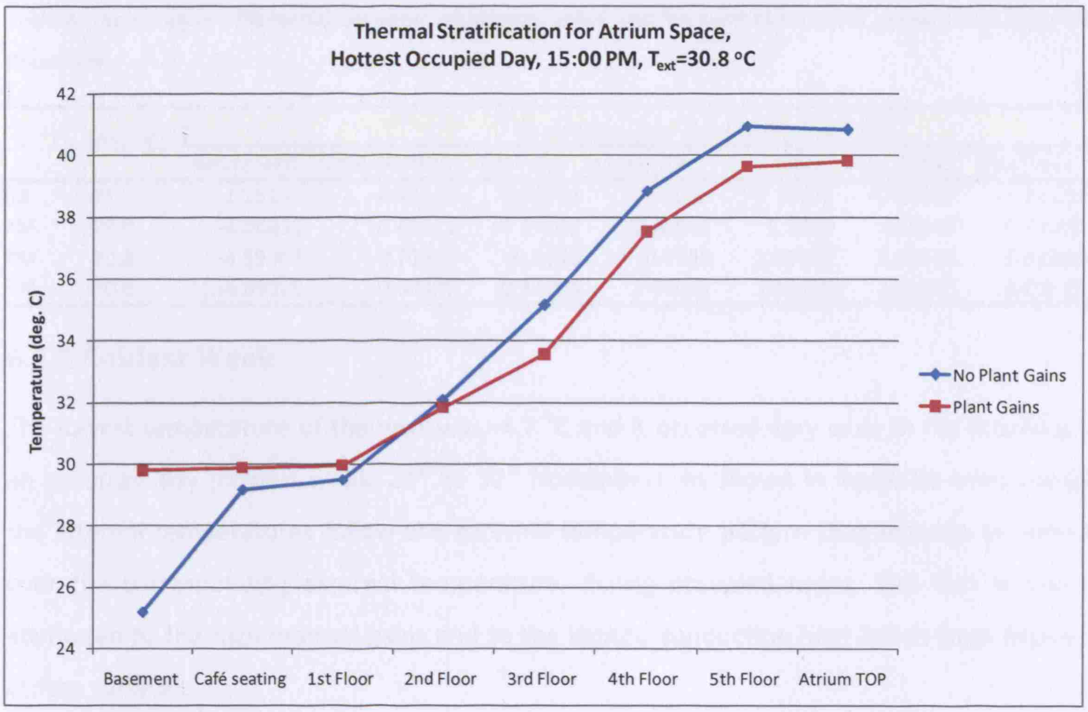

Figure 32. Thermal stratification in atrium space for the hottest occupied hour for the scenarios of 'plant room gains' and 'no plant room gains'

As shown, the running plant room increases the dry bulb temperature in the cafe seating area by only 0,7 °C for the certain hour. The positive effect of the plant room gains on the performance of the stack is more obvious for the higher level atrium. For the same floor level the temperature differential (ΔT) between the 'no plant room gains' and 'plant room gains' scenario is approximately 1 °C for mid and high level atrium (3rd floor to atrium top). And this is just the case for the hottest hour of the day where internal and external temperatures are similar and therefore the stack effect is weaker (see chapter 3.6). As shown in table 8 (related to figures B6 and B7), for the fifth floor the temperature differential between the two scenarios, reaches 4.7 °C when external conditions are less extreme (12:00 PM) while at the same time the temperature differential between the two scenarios for the cafe seating area is only 0,5 °C. Evidently, the more enhanced the stack effect is due to plant room gains, the closer the temperature in the cafe seating area is to the one that would occur without the plant room's existence, even though a large amount of heat gain is released close to that area.

Table 8. Temperature differential between 'plant room gains' and 'no plant room gains' scenarios for the same floor level

Time	T_{ext} (deg. C)	$T_{NO\ plant\ room\ gains} - T_{plant\ room\ gains}$ (deg. C)							
		Basement	Cafe seating	1st Floor	2nd Floor	3rd Floor	4th Floor	5th Floor	Atrium Top
9:00 AM	23.3	-1.16209	-0.35189	-0.38701	-0.30058	-0.18798	-0.07303	-0.01421	0.01585
12:00 PM	29.0	-4.06635	-0.49211	-0.44102	2.48682	2.1259	3.20097	4.71935	4.2067
15:00 PM	30.8	-4.59368	-0.70257	-0.4539	0.2369	1.59593	1.33101	1.32366	1.00176
18:00 PM	30.6	-4.89325	-0.68329	-0.33004	1.44264	1.39429	2.41013	4.00123	3.07345

6.2.2 Coldest Week

The lowest temperature of the year was -4,7 °C and it occurred very early in the morning of an occupied day (coldest week, 24th to 30th November). As shown in figure B8 even though the internal temperatures follow the external temperature pattern they manage to remain over the corresponding external temperature, during occupied hours. This fact is mainly attributed to the high internal gains and to the limited conduction heat losses from exposed atrium surfaces.

6.2.2.2 Thermal Stratification

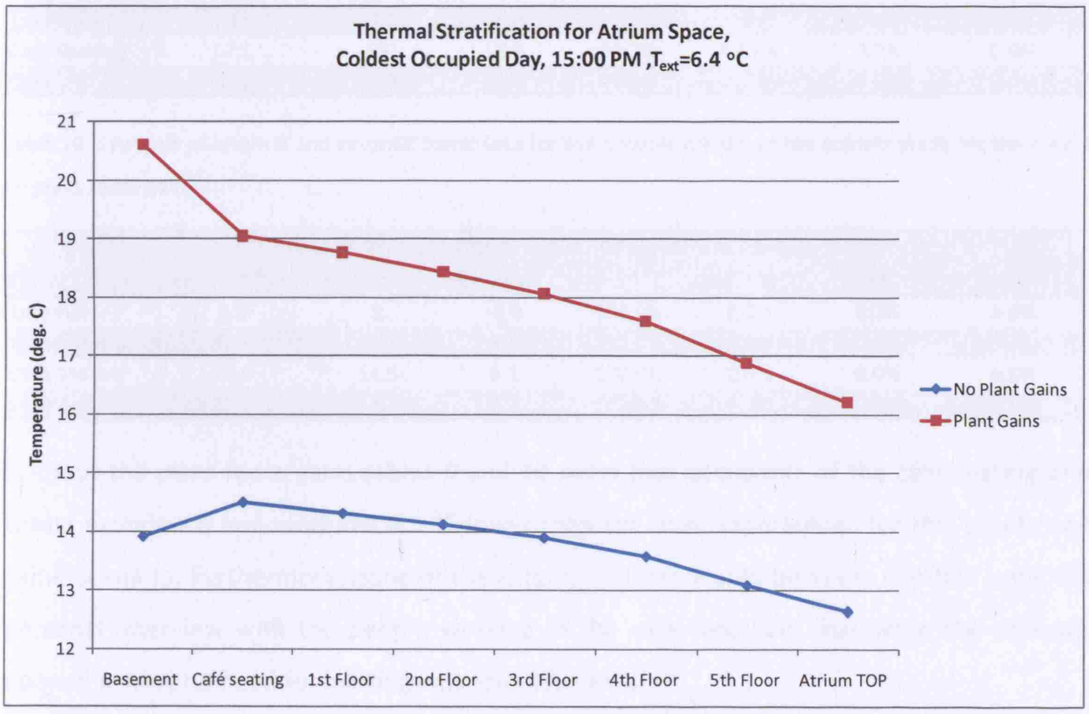

Figure 33. Thermal stratification in atrium space for the coldest occupied day for the scenarios of 'plant room gains' and 'no plant room gains'

The thermal stratification inside the atrium for the coldest occupied day of the year is illustrated in figure 33. The time of day was not the coldest of the day but still it was chosen because it represents better the effect of internal gains to the atrium space.

By comparing figure 33 to figure 32 we realize the importance of the plant room for the atrium cafe area, in heating season. Figures B9 and B10 also help to that. According to Mills (Mills, 1994), atrium spaces have high energy demands for heating. In our case the atrium space can only be treated as unconditioned space therefore no direct heating can be provided. However, it is heated indirectly by the waste heat of the boilers in the basement plant room and manages to stay within comfort limits for 43% of occupied hours for the coldest week while the average temperature was 17.1 °C. Still, the operation of the boilers is independent of any activity taking place in the atrium space as they serve other purposes so no building regulations for the atrium space are violated.

Table 9. Synopsis of internal and external conditions for the occupied hours of the coldest week

Coldest Week, Occupied Hours							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	3.9	8	-4.7	100.0%	0.0%	0.0%	0.0%
Reception	15.1	16.8	11.9	100.0%	0.0%	0.0%	0.0%
Cafe Seating	17.1	19	10.8	57.3%	42.7%	0.0%	0.0%
Cashiers'	16.9	18.8	10.6	57.3%	42.7%	0.0%	0.0%

Table 10. Synopsis of internal and external conditions for the occupied hours of the coldest week for the case of no plant room gains

Coldest Week, Occupied Hours (No plant room gains)							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	3.9	8	-4.7	100.0%	0.0%	0.0%	0.0%
Reception	12.3	13.7	9.8	100.0%	0.0%	0.0%	0.0%
Cafe Seating	12.6	14.5	8.1	100.0%	0.0%	0.0%	0.0%
Cashiers'	12.6	14.7	7.9	100.0%	0.0%	0.0%	0.0%

Without the plant room gains tables 9 and 10 show that occupants of the cafe seating area would experience temperatures 4.5 °C lower than the ones experienced for the 'plant room gains' scenario. Furthermore, none of these temperatures would be in the comfort zone. In a personal interview with the people working in the cafe they said that since the cafe was opened in May no need for heating was found necessary.

None of the temperatures for the reception area are in the comfort zone for any of the two cases. However, receptionists admitted in a conversation that they make use of a personal heating device during heating season, thus confirming our results.

6.3 Effect of Atrium Environmental Conditions on Adjacent Offices

The most efficient way to assess the effect of the atrium on the offices' internal environment is through the estimation of the annual heating and cooling energy demand.

6.3.1 Cooling Energy Demand

As shown in figure 34 the demand for cooling increases with floor level as a result of warm air stratification. Note that any results for the fifth floor are not taken into consideration as the related office has a different floor to ceiling height than the rest of the offices as a result of modeling limitation in TAS. Furthermore, as a top floor room it is affected by external conditions more than other floors do. Some of the fourth floor offices have an exposed roof too.

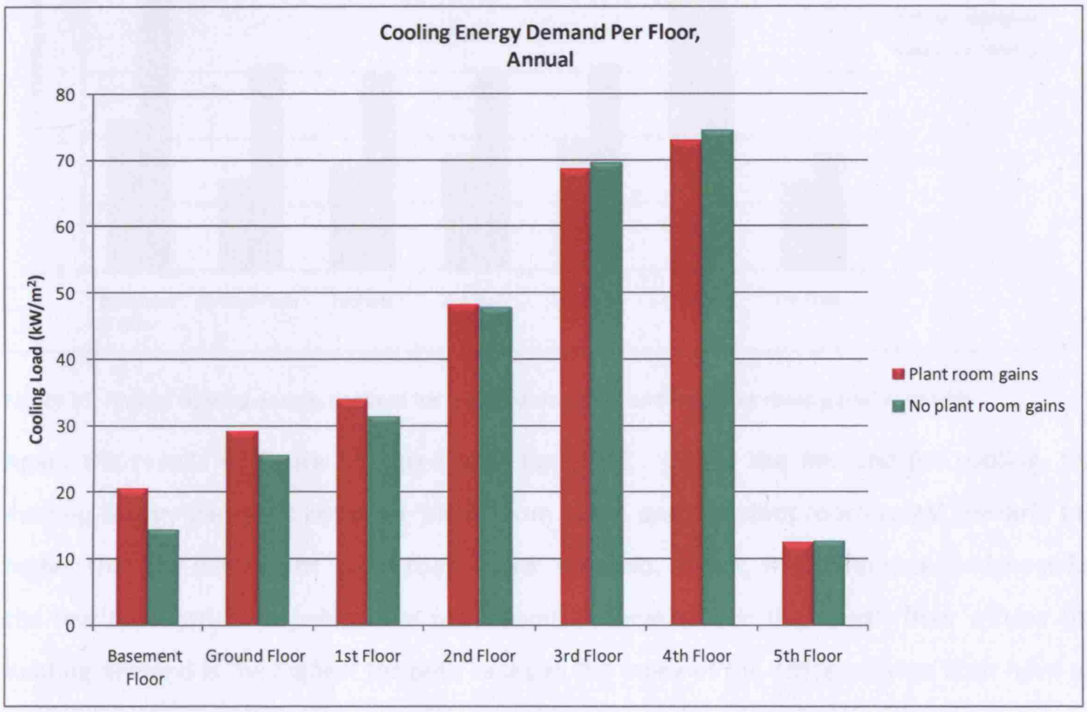

Figure 34. Annual cooling energy demand for 'plant room gains' and 'no plant room gains' scenarios

Someone would expect more cooling energy demand for the basement offices as they are the most adjacent to the plant room, office zone. However, during the evening the plant room operation is stopped and night ventilation is provided to the space through the basement inlet. The cool external air picks up the remaining heat occurring from the plant room's day operation and rises upwards in the atrium thus effectively pre-cooling the basement area.

The existence of the atrium has a very small effect in the cooling energy demand of the offices, meaning that the internal temperature of offices is not severely influenced by it and agrees with the results of figures 67-69.

6.3.2 Heating Energy Demand

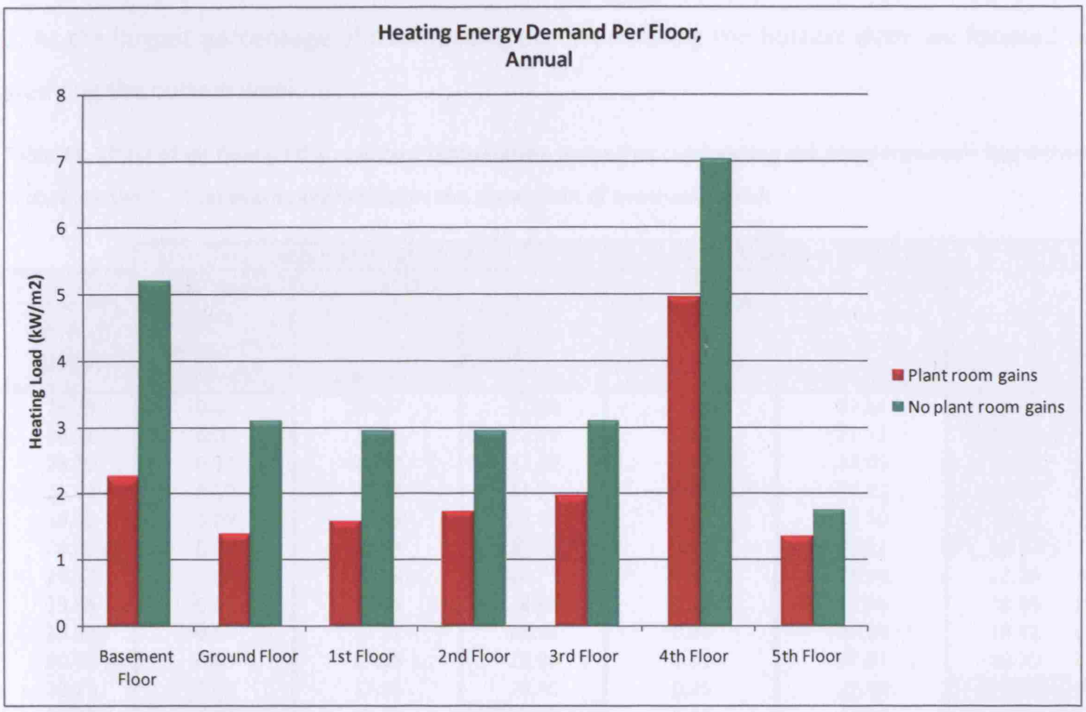

Figure 35. Annual heating energy demand for 'plant room gains' and 'no plant room gains' scenarios

Again the results of figure 35 agree with figure 33. Unlike the demand for cooling, the heating energy demands between 'plant room gains' and 'no plant room gains' scenario are higher that the demand of 'plant room gains' scenario. In fact, this difference is highest for the low level atrium in which the plant room is located. For the fourth floor offices the heating demand is the highest for both cases as the many of the offices of that floor have an exposed roof and walls in some cases.

A more careful observation of energy demand per floor and orientation (figures B13, B14) suggests that the offices on the NE side of the atrium require less cooling during summer and more heating during winter than the other oriented offices do. This is attributed to the fact that the certain offices are opposite the internal façade that contains the outlet therefore it is affected less by the warm buoyant air flow.

6.4 Overheating Risk and Thermal Comfort Analysis for Cafe Seating Area

A more quantitative study of the thermal comfort conditions and the cooling effect from the air flow in the cafe seating area was performed with the help of figure 2 and equations 1 and 2. As the largest percentage of overheating occurred during the hottest week we focused on studying the certain week.

Table 11. Effect of air flow on dry resultant temperature exceeding overheating risk temperatures – highlighted in blue are the T_{res} that eventually fall below the upper limit of overheating risk

	reception to cafe flow			basement to cafe flow		
cafe seating Dry Bulb (deg.C)	reception to cafe seating air flow (m/sec)	T_{res} upper limit for thermal comfort (dry bulb=28 °C)	Reduced T_{res} (deg. C)	basement to cafe seating air flow (m/sec)	T_{res} upper limit for thermal comfort (dry bulb=28 °C)	Reduced T_{res} (deg. C)
28.39	0.02	27.37	27.56	0.31	27.54	26.81
28.51	0.00	27.33	27.59	0.32	27.52	27.09
28.39	0.07	27.32	27.52	0.27	27.49	26.37
28.07	0.10	27.28	27.32	0.23	27.43	26.12
28.50	0.09	27.63	27.88	0.23	27.70	26.73
28.87	0.20	27.84	27.44	0.11	27.81	26.84
29.57	0.00	27.92	28.71	0.28	27.94	28.26
29.85	0.01	27.95	28.88	0.29	27.96	28.33
29.89	0.00	27.97	28.92	0.31	27.98	28.42
30.08	0.03	27.96	29.00	0.31	27.97	28.30
29.79	0.04	27.91	28.80	0.31	27.93	27.85
28.83	0.17	27.96	27.62	0.11	27.96	27.07
29.52	0.14	28.13	28.45	0.11	28.14	27.65
29.69	0.12	28.16	28.71	0.19	28.14	27.76
29.34	0.24	28.13	27.73	0.14	28.15	27.33
29.27	0.22	28.12	27.84	0.14	28.14	27.34
28.07	0.37	28.00	26.58	0.17	27.99	26.43
28.56	0.16	27.83	27.48	0.22	27.84	26.78
29.64	0.05	27.93	28.75	0.24	27.94	27.50
29.91	0.00	28.02	28.98	0.32	28.01	27.78
30.12	0.00	28.04	29.10	0.33	28.03	27.90
29.01	0.06	27.95	28.46	0.34	27.96	27.16
29.32	0.00	27.91	28.57	0.35	27.94	27.32

For the hottest week, all dry bulb temperatures exceeding 28 °C during occupied hours were isolated as well as the corresponding mean radiant and resultant temperatures for the same hour. By imputing 28 °C as dry bulb temperature and the occurring mean radiant temperature for each of the overheating hours in equation 1, the upper limit of the overheating risk expressed in dry resultant temperature was estimated for each of the overheating hours.

For each of the overheating hours the air velocity for the air flow through the cafe entrance and through the basement, into the cafe seating area, was also calculated from TAS results. With the help of figure 1, the equivalent reduction in dry resultant temperature was estimated. After subtracting the equivalent reduction in dry resultant temperature from the dry resultant temperature data occurring from TAS results viewer it was possible to see if the resulting resultant temperature dropped into the overheating risk zone, acceptable for very extreme conditions.

By comparing tables 11 and 12 we can see that overheating occurrences for the 'plant room gains' case are more than for the case without as a result of excess heat gains.

Table 12. Effect of air flow on dry resultant temperature exceeding overheating risk temperatures for the 'no plant room gains' scenario - highlighted in blue are the T_{res} that eventually fall below the upper limit of overheating risk

	reception to cafe flow (No plant room gains)			basement to cafe flow (No plant room gains)		
cafe seating Dry Bulb (deg.C)	reception to cafe seating air flow (m/sec)	T_{res} upper limit for thermal comfort (dry bulb=28 °C)	Reduced T_{res} (deg. C)	basement to cafe seating air flow (m/sec)	T_{res} upper limit for thermal comfort (dry bulb=28 °C)	Reduced T_{res} (deg. C)
28.05	0.07	27.06	27.09	0.19	27.06	27.09
28.01	0.07	27.42	27.42	0.20	27.42	27.42
28.28	0.11	27.60	27.48	0.12	27.59	27.73
28.98	0.07	27.68	28.17	0.17	27.68	28.17
29.15	0.07	27.70	28.27	0.17	27.70	28.27
29.47	0.07	27.73	28.46	0.13	27.73	28.46
29.41	0.07	27.70	28.41	0.17	27.70	28.41
29.10	0.06	27.64	28.20	0.10	27.64	28.20
28.09	0.10	27.68	27.61	0.19	27.67	27.71
28.81	0.07	27.87	28.27	0.21	27.87	28.27
29.04	0.08	27.89	28.41	0.19	27.89	28.41
28.44	0.16	27.87	27.42	0.18	27.85	28.07
28.44	0.15	27.85	27.55	0.15	27.83	28.05
28.39	0.11	27.59	27.58	0.20	27.59	27.78
28.43	0.11	27.65	27.61	0.19	27.64	27.86
28.64	0.07	27.64	27.96	0.24	27.64	27.96
28.57	0.00	27.55	27.83	0.33	27.55	27.08

However, the same excess heat gains from the running plant room that contribute to the increase of overheating occurrences also reduce opportunities for the stack to be reversed during hot spills by maintaining internal temperatures higher than external temperatures for longer and therefore encourage air mobility in, at least, the lower atrium.

Comparison of the magnitude of air flow for the two case studies is allowed in figures B15, B16 in appendix.

6.4 Effect of café protection border on thermal comfort

In reality the café area is surrounded by a ~ 1.2 m high protection border as the café space is a mezzanine floor that communicates with the basement. Another simulation was run in order to investigate the impact of this protection border on occupant comfort.

Table 13 gives the synopsis of the annual results of this simulation for the external and main occupied areas.

Table 13. Synopsis of annual internal and external conditions for the café protection border case

Annual, Occupied Hours, including cafe protection border							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	13.9	31.1	-4.7	70.3%	22.0%	6.6%	1.5%
Reception	19.5	29.4	9.5	28.8%	64.9%	6.3&	0.5%
Cafe Seating	20.9	30.2	9.4	14.8%	76.8%	8.4%	1.4%
Cashiers'	21	30.3	9.5	14.6%	76.7%	8.8%	1.4%

If compared to table 6, table 13 suggests that the protection border seriously impacts human comfort during winter but has less impact on the summer overheating occurrences. This is attributed to the fact that during heating season the basement is the only means of heating for the café area and the protection border impedes the weak warm air flow from the basement to effectively enter the café area. Still, the thermal comfort conditions are better than those for the 'no plant room gains' scenario.

The same effect but with less impact also happens during cooling season, as shown in table 14.

Table 14. Synopsis of internal and external conditions for the occupied hours of the hottest week for the case of the raised café protection border

Hottest Week, Occupied Hours, including cafe protection border							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	26.6	31.1	18	0.0%	25.4%	76.4%	41.8%
Reception	26.1	29.4	19.8	0.0%	29.1%	70.9%	27.3%
Cafe Seating	26.9	30.2	20.6	0.0%	23.6%	76.4%	41.8%
Cashiers'	27.0	30.3	20.7	0.0%	23.6%	76.4%	43.6%

During cooling season, a large amount of air enters the atrium space through the basement inlet and the café entrance. However, because of the enhanced stack only a small margin is left for the air to disperse and enter the café space due to change in volume. Furthermore, the temperature difference between external and internal is smaller than it is for winter and therefore the possible effects of the basement air flow on the café are less sensible.

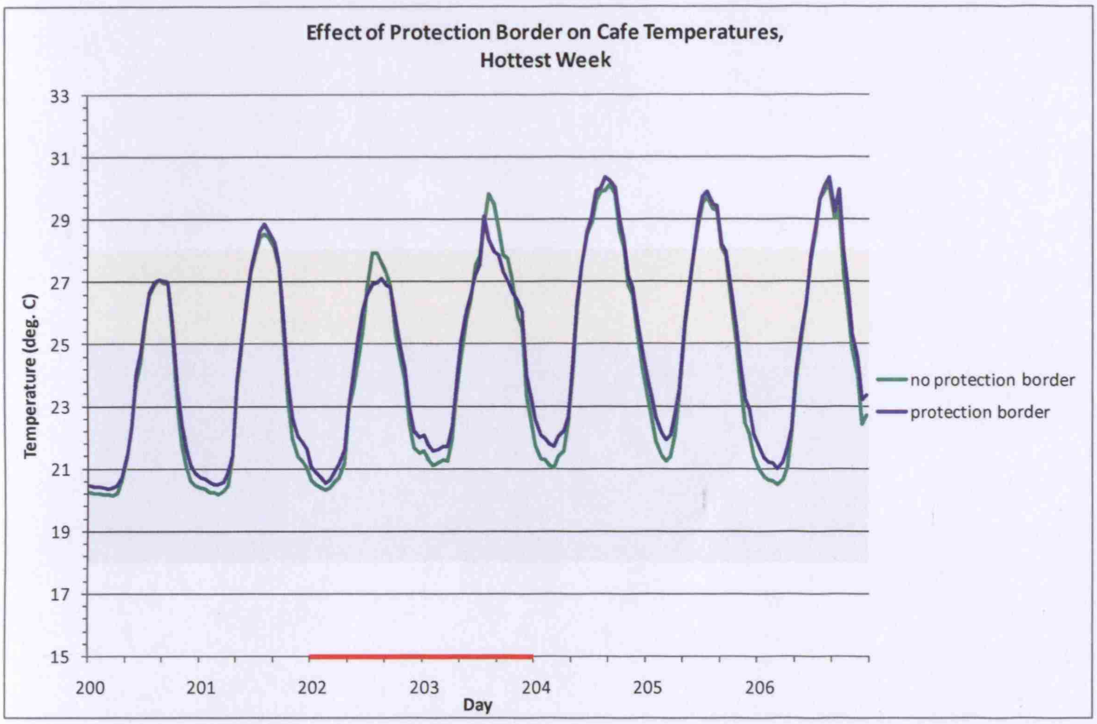

Figure 36. Effect of protection border on café diurnal temperature variation for the hottest week – red line indicates the weekend

Figure 36 suggests the possible effects of the protection border on the diurnal temperature variation in the café seating area by comparing the cases . As observed, for the case of the raised protection border night ventilation is less effective. This is attributed to the fact that air is now trapped in the café area and the shut café entrance does not assist its removal. During occupied days the temperatures in the café for the case of the raised protection are again higher than the ones for the case lacking the border. However, because of the open café entrance the temperature difference for the two cases is much smaller.

Chapter 7

7.0 Analysis of Monitoring and Simulation Results

The hottest week in the monitored interval occurred between the 26th of June and 2nd of July with the 1st of July being the hottest day reaching 28.8 °C. This week is studied more thoroughly as it can produce more representative conclusions on overheating risk.

7.1 Monitoring Results

According to table 15 only 8% of the temperatures recorded for the cafe and cashiers area exceeded 28 °C and only for very hot days. However, their largest percentage was in the overheating risk temperature band of 25-28 °C when for the external temperatures the largest percentage was in the thermal comfort zone. The reception area managed to stay within comfort limits for almost 100% of occupied hours. All temperature variations follow the external pattern but the temperatures, themselves, differ from the external temperature values following a rather stable differential (figure 23).

Table 15. Synopsis of internal and external conditions for the occupied hours of the hottest monitored week

	Hottest Monitored Week, Occupied Hours						
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	20.5	29.1	15.1	19.1%	72.2%	8.7%	5.0%
Reception	21.1	25.2	18.6	0.0%	99.7%	0.3%	0.0%
Cafe Seating	25.8	29.3	23.6	0.0%	24.7%	75.3%	8.0%
Cashiers'	26.1	29.4	24.3	0.0%	9.0%	91.0%	8.0%

Figure 37 is closely related to figure 23 and helps understand the induced stack effect during different times of day and weather conditions. The calculations were made with the help of equation 5.

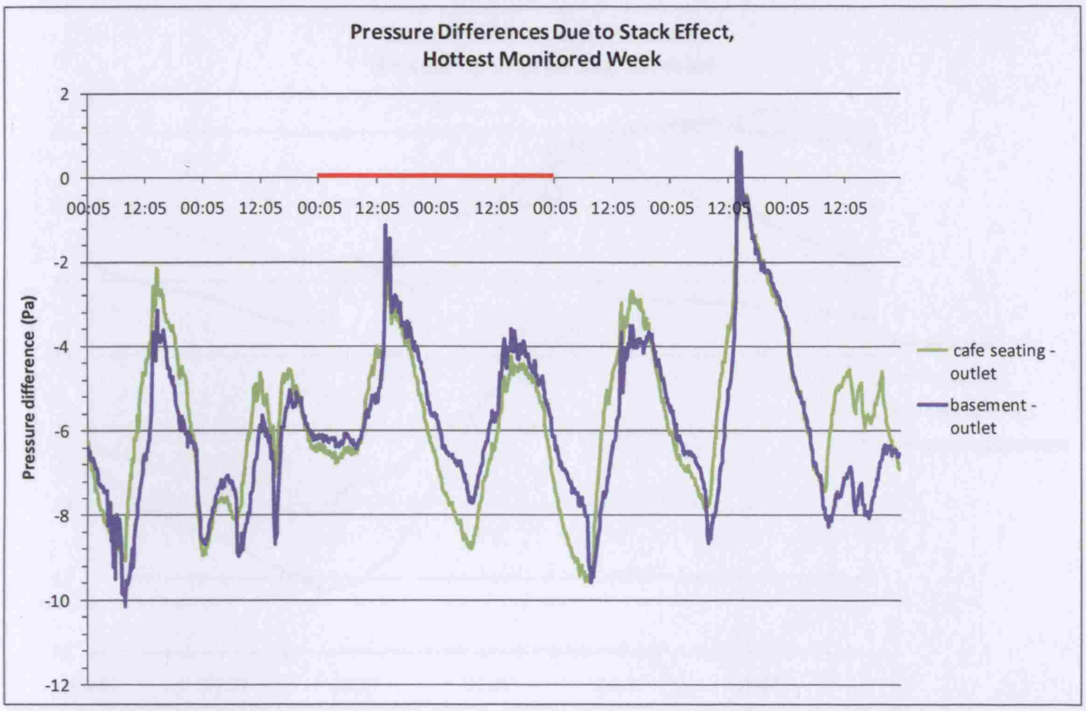

Figure 37. Pressure differences due to stack effect for vertical height difference of Δz=22m and Δz=25.5 m between café seating-outlet and atrium basement-outlet, correspondingly, during hottest monitored week – red line indicates the weekend

During weekdays the stack is stronger for the basement than it is for the seating area because of the plant room gains, while on weekends when the plant room has cooled down the opposite happens. For both cases the stack is more efficient very early in the morning when temperature differential between internal and external is greatest. Once the plant room is activated at 07:00 AM the stack is driven primarily by the temperatures in the atrium basement, but after approximately 12:00 AM when the café seating area presents higher temperatures as explained earlier, the stack is primarily driven by the temperatures in the café seating area, On the hottest day of the week the stack was reversed (positive Δp values, see chapter 3.6) right at the time when external temperature exceeded internal temperatures.

7.2 Hottest Day

The occupancy and internal gains' effects on internal temperatures are more clearly illustrated in figure 38. This presents the hottest monitored day during which at some time the external temperature managed to exceed the internal temperatures.

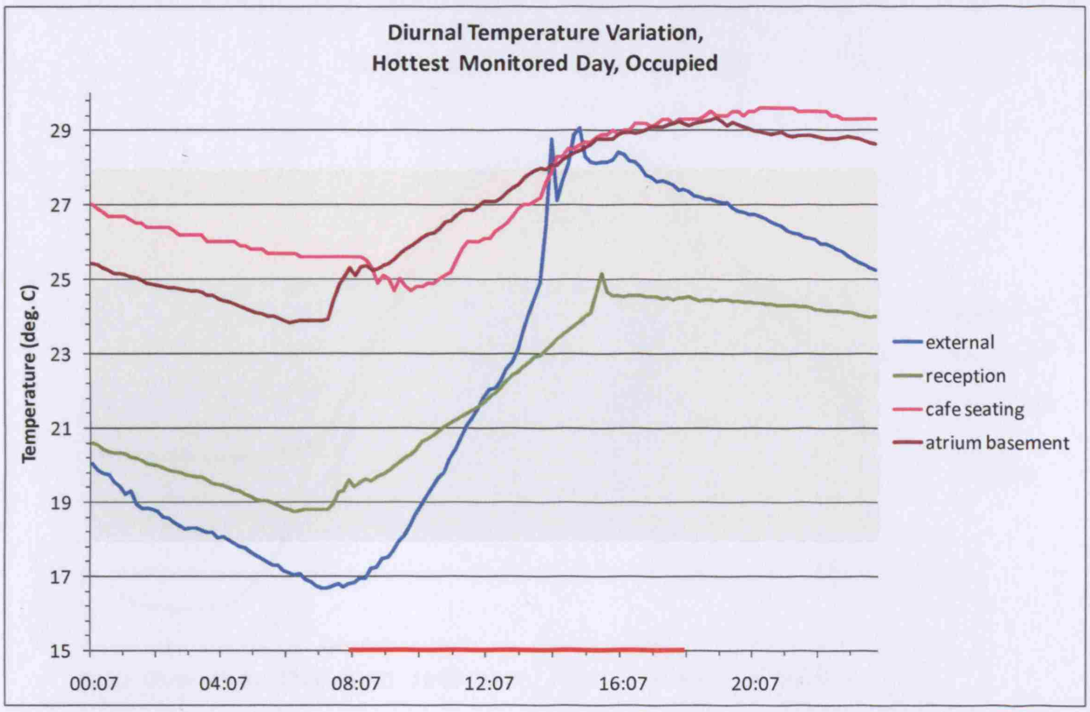

Figure 38. Diurnal temperature variation for external and key areas for the hottest monitored occupied day - red line indicates the occupied hours

A similar to the monitored hottest day was chosen from TAS and was used to estimate the air flow for the hottest monitored day (figure 39). Although peak and lower temperatures are similar for both cases, TAS results give a smoother illustration of the building's thermal performance. That is mostly due to the difference in monitoring intervals for the two cases. TAS Manager gives hourly results while the data loggers give results for every 10 minutes thus giving more varying patterns. Furthermore, the temperature in the morning starts inclining at approximately 05:00 A.M. for TAS while in monitored results inclination starts at 08:00 AM. Also, in the case of TAS temperature declines at a higher rate in the afternoon. Nevertheless, in both cases the peak temperature is achieved at approximately the same time.

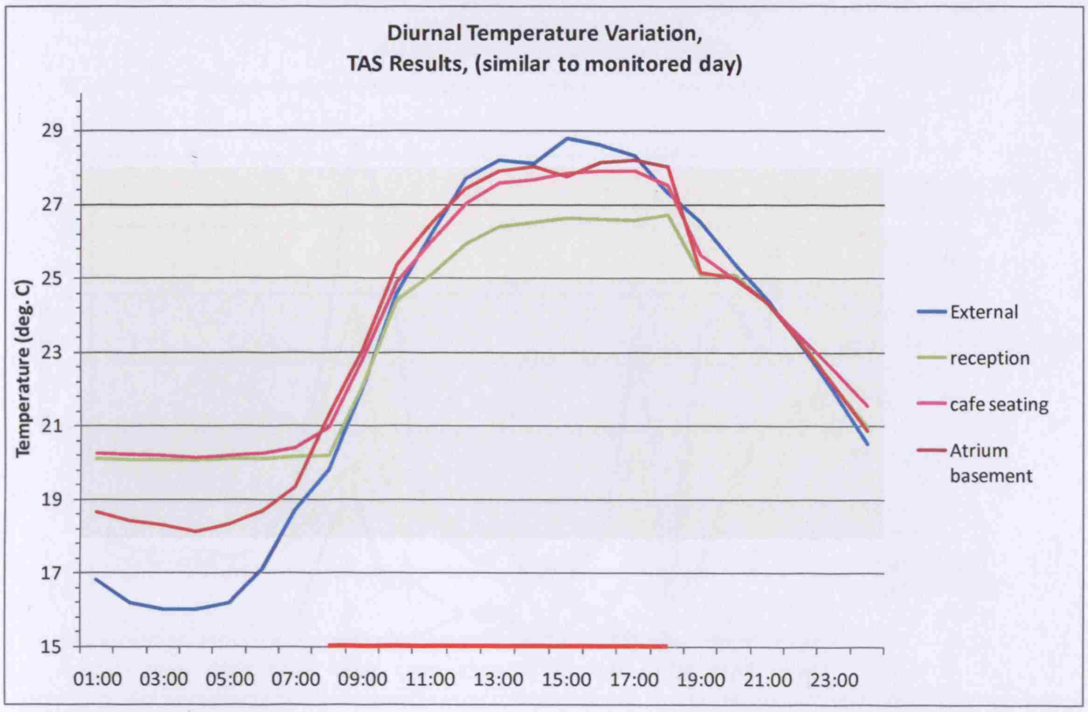

Figure 39. Diurnal temperature variation for external and key areas for a similar to the hottest monitored occupied day, obtained from TAS simulation - red line indicates the occupied hours

7.2.1 Air Flow Study

As expected, figure 40 suggests a reverse flow between 11:30 PM to 17:30 PM when the external temperature exceeded the internal temperature.

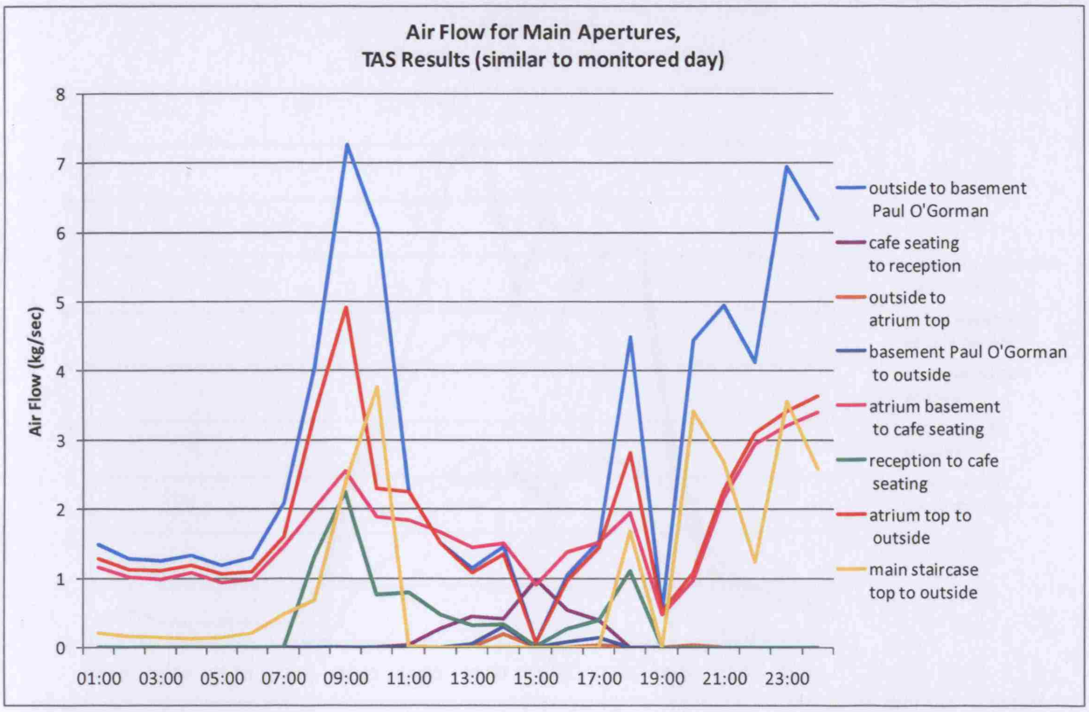

Figure 40. Air flow pattern for similar to monitored hottest occupied day obtained from TAS simulation

During that time air was entering the atrium space through the outlets and escaped through the basement inlets, after flowing through the reception area. Nevertheless, the reverse flow remained weaker than the design air flow.

If compared to the air flow occurring in a typical day (figure 41) the air flow for occupied hours in figure 40 might seem very weak. However, if the same flow is compared to the flow in figure C2 (appendix) the positive contribution of the plant room heat gains to the stack can be evaluated. During hot spills the heat released from the plant room manages to create a weak air flow in the cafe seating level by maintaining the internal temperature at that level higher than the external one for longer. Without the plant rooms' contribution the air would remain rather still.

7.3 Design Air Flow

In a typical day (figure C3, appendix), for which the ambient external temperature remains lower than the internal temperatures the air flows according to the design pattern.

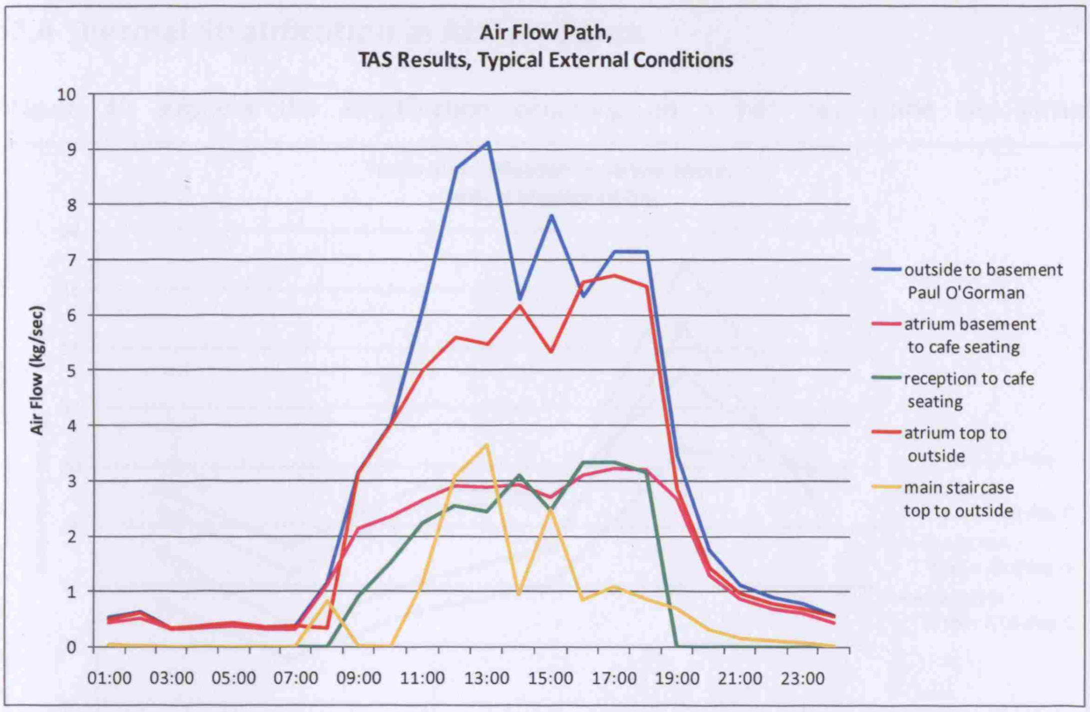

Figure 41. Air flow pattern for a typical occupied day obtained from TAS simulation

Once the cafe entrance is opened at 08:00 AM a sudden very strong pull is exerted on the air flowing inside the building in an effort to bring density equilibrium in the two spaces. By noon this density differential is decreased and the temperature differential between external and internal temperature is also decreased. However, as shown in figure C3 (appendix) because the plant room gains create a slightly higher temperature differential than if the plant would be shut (figure C4, appendix), the amount of air entering the cafe seating area through the cafe entrance and through the basement is also higher. Greater air flow, in cooling season, means enhanced perception of thermal comfort as it contributes to lowering of the dry resultant temperature as proven earlier in chapter 6.4.

7.4 Thermal Stratification in Atrium Space

Figure 42 suggests the stratification occurring on a hot day inside the atrium.

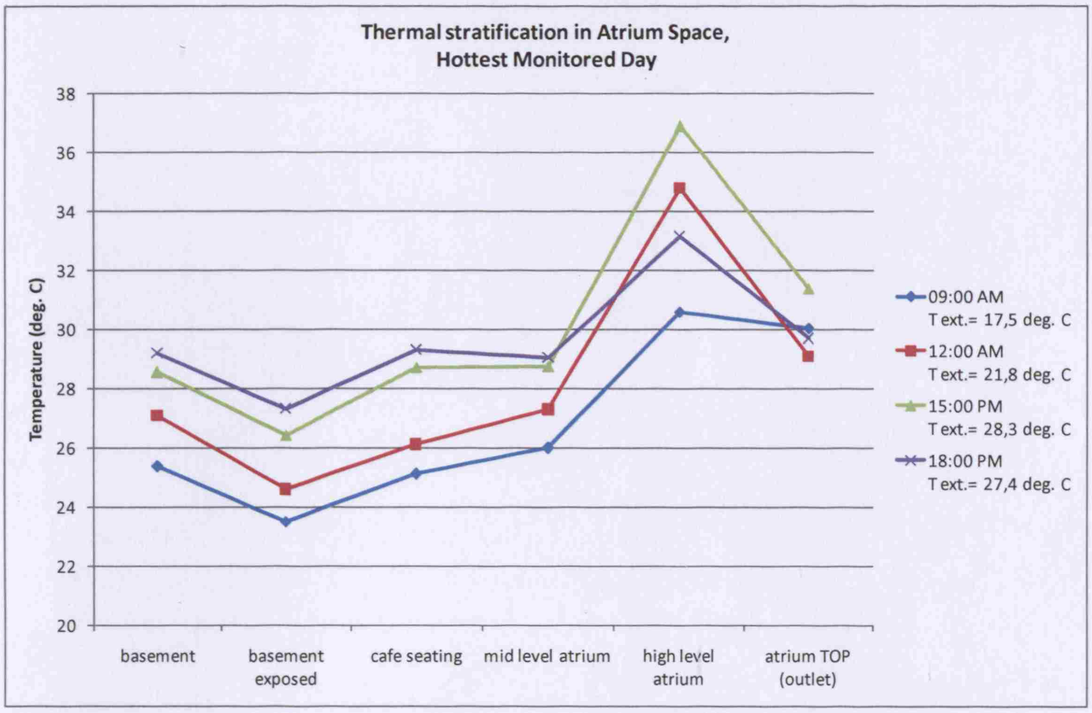

Figure 42. Thermal stratification in atrium space for the hottest monitored occupied day

Before noon the temperature in the cafe seating area is lower than the one occurring in the basement by 0,5 to 1 °C but as internal gains pile up and external temperature increases during the day, the temperature in the cafe seating space becomes equal to or slightly higher (0.2 °C) to that of the atrium basement. The smaller temperature differential between internal and external temperatures at mid-day also affects the performance of the stack; the stack pull is degraded and the amount of air purged outside is decreased as well thus resulting to such high temperatures in the café seating area.

It must be noted that from approximately 12:00 PM to 16:00 PM the high level atrium is exposed to sunlight. Therefore, the data logger at that level was affected by solar gains and gives non-objective, higher temperature values for that time interval.

Chapter 8

8.0 Modeling Limitations

The integrity of our simulations was subject to modeling limitations that had to be followed either for simplicity reasons, or because of software faults. However, the limitations and their impact on results were recognized and identified as follows:

Urban heat island: The case study building is very close to the eye of the heat island but still it is not taken into consideration in the weather file used for simulation. Therefore, the significant effect it can have on night ventilation could not be studied in the results occurring from the simulation software. Since monitored data include the heat island effect the reliability of the conclusions occurring from the use of TAS data to study the air flow of a similar to simulated monitored day lack of reliability.

Symmetry of floor to ceiling height for host-buildings: The atrium space is hosted by three different buildings all with different floor-to ceiling heights. For the medical school buildings floor to ceiling height also differs from one floor to another. For modeling simplicity and symmetry means all floor to ceiling heights for all three buildings were set to be the same as the ones for Paul O'Gorman building. However, since our primary purpose was to study the atrium space it was important to keep the total building height so as to maintain the available space for stratification inside the atrium the same as in reality.

Atrium offices' aperture schedule-size: as probably noticed from figures 18 and 20 the apertures' location and size is variable throughout the medical sciences buildings facades. Apart from this their operation schedule is variable and unpredictable too. In the simulation software symmetrical shapes, schedules and locations were used in an effort to achieve results that would be clearer and easier to interpret.

Air flow through café protection border: a simulation with the café protection border was run but because of the initial model's nature the air flow to the café area from the atrium basement was not given in TAS results. Therefore, the certain air flow could only be studied thoroughly for the certain case, which is closer to reality. Even so, an approximation of the air flow effect on human comfort could be estimated for the case of no protection border.

Occupancy schedule: a stable annual schedule was applied for occupancy and internal gains even through in reality this can occasionally vary.

Thermal mass effects in TAS: the effects of thermal mass, like for example shifting and lowering of peak internal temperature, for the reception area were not efficiently given in TAS results for the reception area. Nonetheless, the effects of night ventilation on radiant temperature were successfully given for the atrium space.

Chapter 9

9.0 Conclusions

The basic aim of this study was to analyze and assess the thermal performance of the complex case study atrium, described above, and the effect it has on human comfort but also possible impacts of global warming on its performance. Individual but also combined analysis of field and simulation measurements helped us draw conclusions for the case study atrium but also conclusions that correspond to atrium buildings in general.

9.1 General Conclusions

Probably the most significant conclusion drawn in this study is that large heat gain sources in an atrium space are critical during hot spills as they can help maintain internal temperatures higher than external for longer and limit the risk of stack reversal. However, much consideration needs to be given to the positioning of these sources as even though they can help maintain adequate ventilation rates they can also significantly increase the overheating risk. In attached atria, for example, this heat could be provided by solar gains from glazed surfaces, while for core atria waste heat for a plant room could do that.

Furthermore, the exploitation of waste heat gains from plant rooms can form an energy efficient (and therefore cost-efficient) strategy to effectively heat large spaces like atria. Especially in atria with almost no solar gains at all, like core atria, locating a plant room or another major heat gain source whose primary purpose is other than providing heating, close to an area with heating demands, could be a very beneficial solution.

As simulations run with a DSY weather file have shown, naturally ventilated buildings that perform rather satisfying today are very likely to present increased overheating incidents in the future as a result of increase in hot spills.

Also, thermal modeling software have become more accurate and user friendly over the past years. Results obtained from these software on existing or new buildings can help predict actual performance and also climate change impacts on building performance. Especially, for naturally ventilated buildings whose performance is more unpredictable and susceptible to these changes thermal modeling software have become a huge asset for the building industry.

Finally, night ventilation proves to be a powerful cooling strategy for office buildings. Because it is applied during the evening when internal and external temperatures are greater and the building is unoccupied its cooling capacity is enhanced without any impact on occupants' comfort. By pre-cooling the building's structure, comfort perception during the day is enhanced through radiant cooling.

9.2 Conclusions for Case Study

A very interesting conclusion involving the case study atrium was drawn from table 8. As established, the more enhanced the stack effect is due to plant room gains the closer the temperature in the cafe seating area is to the one that would occur without the plant room's existence, even though a large amount of heat gain is released close to that area.

Furthermore, analysis of the heating period data showed that during that period the thermal conditions in the café area can prove satisfying for occupants that are willing to adapt to temperatures 1 or 2 °C under the lower comfort limit.

However, as simulations with the DSY weather file have shown, if global warming keeps enhancing then overheating risk could increase dramatically for the café area.

Measurements of the cooling energy demands, from TAS, for the atrium offices have shown that these are not strongly influenced by the atrium's thermal environment during summer. Charts C6-C8 in appendix represent monitored data and confirm this conclusion.

Nonetheless, measurements of the atrium offices' heating energy demand show that it increases with floor level as a result of lack of internal gains and also for the case of the 'plant room gains' scenario need for heating is more reduced because of these plant room gains.

However, the impact of the warm buoyant air flow is less significant for internal façade offices located opposite the outlets since air is drawn away from them. Therefore, during heating season more heating energy is required to condition them, while during cooling season less cooling energy is required.

Also, night ventilation helps lower mean radiant temperature effectively thus reducing overheating risk for the next day. However, in reality the impact of night ventilation on mean radiant temperatures in the Paul O'Gorman building could be less significant since it is located near the eye of urban heat island and the weather files used for thermal simulations don't take into account this effect.

Both monitored and simulation results have shown that the circulation space of the Paul O'Gorman building including the main staircase and reception area perform ideally during cooling season and can compete with any air-conditioned building. Contrarily, during heating season the lack of internal gains results to thermal comfort conditions that are outside the comfort range.

As concluded from TAS results the air flow from the atrium basement to the café area is stronger for the 'plant room gains' scenario than it is for the 'no plant room gains' scenario. Even though a modeling limitation prevented us from obtaining data for the air flow from the basement to the café area for the simulation with the ~ 1.2 m high protection border, still proof is given that the existence of the plant room does enhance air flow even during hot spills for the café area.

Nevertheless, the simulation including the raised protection border showed that its existence prevents heat gains from the atrium basement to enter the café area. This fact has serious effects on the human comfort during heating season as it prevents the weak warm buoyant air from the basement to enter the café area and provide heating.

The café entrance plays a very important role in the cooling of the atrium space by allowing excess air flow into the atrium space. However, during unoccupied hours, due to operational & security reasons it has to be kept shut during the evening and weekends thus reducing the ventilation cooling capacity. This fact deprives a significant opportunity of the café ambient air and mean radiant temperature to reduce during unoccupied hours and therefore enhances overheating risk during occupied hours. This conclusion is very obvious in monitored results.

9.3 Further Research

From the case study atrium many important studies could be further conducted. Figures B13 and B14 in appendix promise interesting results on the further study of energy consumption of offices not only for different atrium level but also for different orientation.

Furthermore, an occupant survey studying the occupant perception of thermal comfort in a naturally ventilated environment on which they have no control at all (i.e. openable windows) could be established. The fact that the café area is often in or even over the overheating risk makes this survey even more appealing.

Also, a CFD model accompanying further research could help to a qualitative view of all issues concerning thermal performance and thermal comfort in the atrium space.

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Software Tools Used:

Adobe Photoshop CS2

Google SketchUp Pro 6,

HOBOWare Pro

Microsoft Office

TAS, Thermal Analysis Software

Appendices

Appendix A

Appendix A:

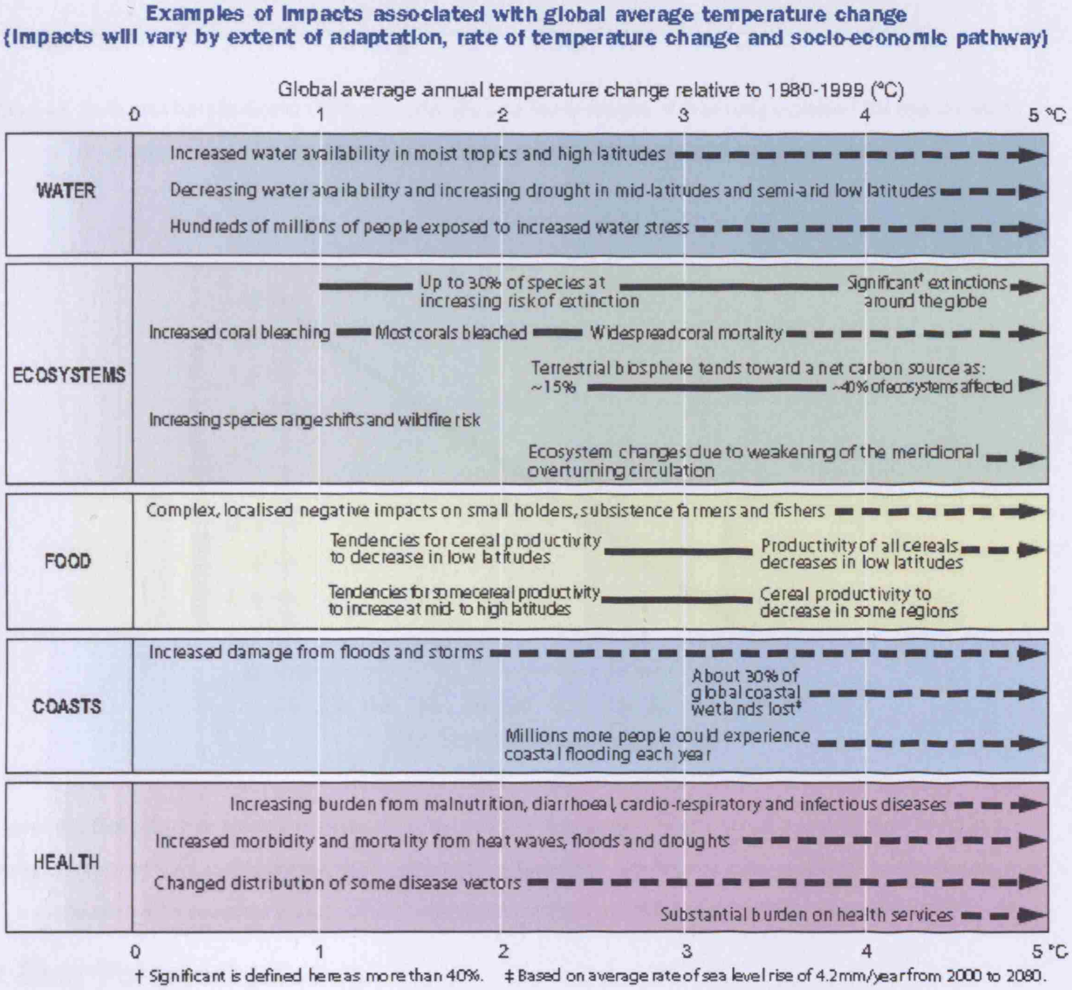

Figure 43. Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric CO_2 where relevant) associated with different amounts of increase in global temperature in the 21st century. The black lines link impacts; broken arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of text indicates the approximate level of warming that is associated with the onset of a given impact. Quantitative entries for water scarcity and flooding represent the additional impacts of climate change relative to the conditions projected across the range of SRES scenarios A1F1, A2, B1 and B2. Adaptation to climate is not included in these estimations. Confidence levels for all statements are high (IPCC, November 2007).

Figure 44. Dots and bars indicate the best estimate and likely ranges of warming assessed for the six SRES marker scenarios for 2090-2099 relative to 1980-1999. (IPCC, November 2007)

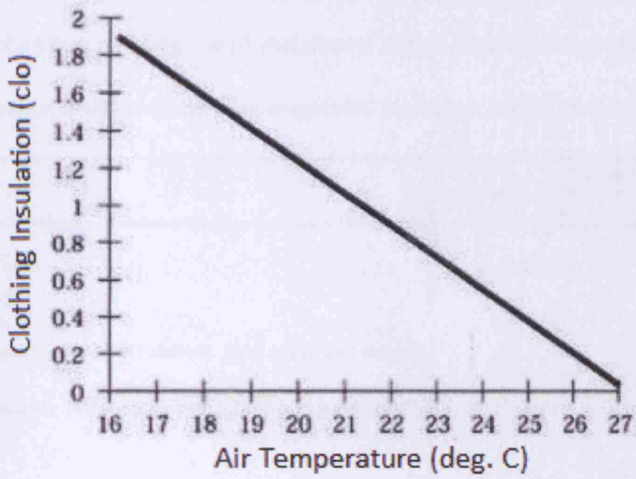

Figure 45. Clothing insulation necessary for neutral thermal sensation of sedentary persons (1 Met) in a thermally uniform still-air environment with 50% relative humidity. For higher activity levels the temperature at a clo level can be reduced about 1.4 per met increase (Larry G. Berlung, 2001 cited in Awbi, 2002).

A1.1 Body Thermoregulation

The vital organs of the human body, contained within the body core, need to be maintained within a very narrow range of temperature critical for their proper functioning. The procedure to achieve this is called body thermoregulation. Through complex mechanisms the hypothalamus, located in the brain, manages to maintain the body core temperature to constant levels, which under normal conditions is approximately 37 °C. In extreme activities it can be as high as 39.5 °C as it depends on activity i.e. increases with increase in metabolism (Awbi, 2002).

Table 16. Metabolic rates of different activities (The Engineering Toolbox, 2005)

Activity	Metabolic rates (M)	
	W/m^2	Met
Reclining	46	0.8
Seated relaxed	58	1.0
Standing relaxed	65	1.1
Sedentary activity (office, dweling, school, laboratory)	70	1.2
Standing, light activity (shopping, laboratory, light industry)	93	1.6
Standing, medium activity (shop assistant, domestic work)	116	2.0

Despite changes in the ambient temperature core temperature is maintained constant for different levels of activity (table A2). This is achieved through thermo-regulating mechanisms such as sweat (evaporative cooling) and increased blood flow to the skin (vasoligate).

Table 17. Thermal resistance of different clothing ensembles (Anon n.d. cited in Awbi 2002)

Clothing ensemble	Clothing Values (I_{cl})	
	m^2 K W^{-1}	(clo)
Nude	0	0
Shorts	0.015	0.1
Typical clothing ensemble: briefs, shorts, open-neck shirts with short sleeves, light socks and sandals	0.045	0.3
Light summer clothing: briefs, long lightweight trousers, open-neck shirt with short sleeves, light socks and shoes	0.08	0.5
Light working ensemble: light underwear, cotton work shirt with long sleeves, work trousers, woolen socks and shoes	0.11	0.7
Typical indoor winter clothing ensemble: underwear, shirt with long sleeves, trousers, jacket or sweater with long sleeves, heavy socks and shoes	0.16	1
Heavy traditional European buisiness suit: cotton underwear with long legs and sleeves, shirt, suit including trousers, jacket and waistcoat, woollen socks and heavy shoes	0.23	1.5

The sensation of thermal comfort is given both by the core temperature and skin temperature. However, while the core temperature remains rather constant for a wide range of ambient temperatures, skin temperature can be different for different parts of the body as a response to changes in the environment (Awbi, 2002).

A1.2 Heat Balance of The Human Body

The ideal situation for heat exchange conditions of the human body is when balanced is achieved between heat production (metabolism) and heat output of the human body (Banhidi & Biro, 2000). This means Individual thermal sensation and productivity are optimal when the rate of heat production in the body by metabolism and performance of external work are equal to the heat loss from the body to the environment by the processes of evaporation, respiration, radiation, convection and conduction from the surface of the clothing (Awbi, 2002). Thus occurs the heat balance equation:

$H - Ed - E_{sw} - E_{re} - L = K = R + C,$ (A1)

where, according to Banhidi and Biro (Banhidi & Biro, 2000):

H = the internal heat production in the human body

Ed = the heat loss by water vapour diffusion through the skin

E_{sw} = the heat loss by evaporation of sweat from surface of the skin

E_{re} = the latent respiration heat loss

L = the dry respiration heat loss

K = the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing)

R = the heat loss by radiation from the outer surface of the clothed body

C = the heat loss by convection from the outer surface of the clothed body

Fanger's PMV-PPD thermal comfort prediction method solves heat balance equations for the human body and is generally implemented on a computer. It is considered as a state-of-the-art thermal sensation model (Fountain & Huizenga, 1997). Readers are advised to read the books of Fanger and McIntyre for further details on the heat balance equation.

A2.1 Control of Summer Overheating

With the current climatic conditions the cooling capacity of natural ventilation is around 30-40 W/m^2 per day. According to CIDSE (CIBSE AM10, 2005) the three main features in the design and use of a building that affect summer conditions are:

- Solar control
- Levels of internal gains from occupants, lighting and appliances
- Comfort expectations

A2.1 Solar control

In order to prevent overheating from excessive solar gains, Part L2 of Building Regulations has set some compliance procedures. The most efficient measures for achieving solar control involve control of direct solar radiation and spectrally selective transmittance of glazing materials. The measures specified by CIBSE (CIBSE AM10, 2005) are:

- Size and orientation of glazed areas
- Tints, films and coatings in/on the glass
- Blinds
- Overhangs, side fins and brise-soleil

In the design procedure much consideration should be given to climate change predictions and how they can affect the performance of the building but also to the heat island effect.

A2.2 Internal Gains

The major internal heat gain contributions in buildings come from occupants, lighting and other appliances like printers and computers. In order to ensure adequate comfort at all times the coincidence of these gains should be minimized and more attention should be paid to daily average gains rather than peak gains.

Occupants

Occupant density can vary throughout a building and throughout the day depending on its use. Therefore, consideration should be given to the occupancy density and schedule of a building so as to make an accurate assessment of the potential overheating.

When assessing the overheating risk of naturally ventilated buildings attention should be paid to the fact that heat emissions from occupants vary according to the level of activity (CIBSE AM10, 2005). As shown in figure A4 sensible heat emission which is a major contributor to internal gains reduces significantly as the internal temperature rises. Thus, if attention is not paid to this fact the overheating risk could be overestimated.

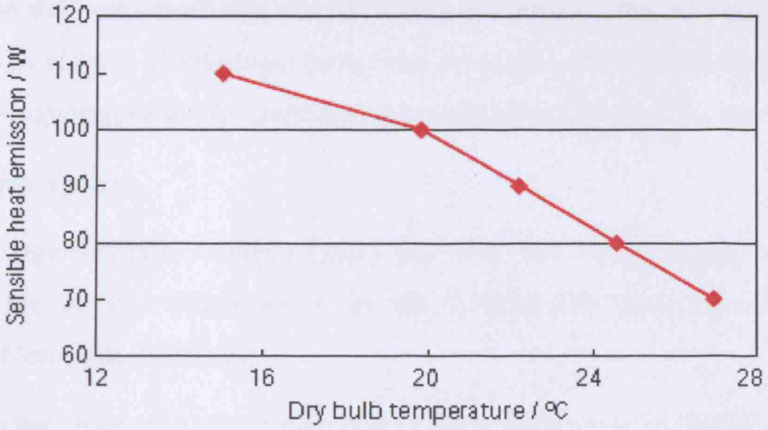

Figure 46. Relationship between temperature and heat emission (CIBSE AM10, 2005 p.5)

Lighting

Lighting is another important source that contributes to potential overheating which however is easier to control. This could happen through efficient light source specification and dimming or switching when daylight levels are sufficient. Effective lighting controls could significantly reduce overheating risk in perimeter spaces during periods of strong sunshine, by minimizing coincidence of high gains (CIBSE AM10, 2005).

The impact of any shading devices on daylight levels should also be taken into consideration. In cases where occupants need to control glare different devices should be provided for this case from the devices used for solar gain.

Equipment

Over areas of 1000 m^2 loads occurring from equipment rarely exceed 15 W/m^2, although for local workstations these can peak to 20-25 W/m^2. In specialist applications like dealer areas these loads could be further exceeded(CIBSE AM10, 2005). In order to prevent overheating local extract point should be provided adjacent to high heat gain equipment.

A3.1 Energy Saving Opportunities in Atria

A3.1.1 Lighting

Atria provide opportunity for daylight penetration into deep plan buildings. Adequate amount and quality of light is available at the occupied spaces of the atrium but also at the spaces adjacent to the atrium, leading to significant savings on energy and to occupant satisfaction.

Depending on the strength of light wanted inside the atrium different external and internal shading devices but also glazing types have been developed. These solar control elements are critical in preventing glare and/or overheating resulting from excess solar gain.

A3.1.2 Buffer Space

Atria act as large habitable insulation layer between their host buildings and the outside. Apart from the obvious improvement in the U-value, this buffering can be enhanced according to Mills (Mills, 1994) by:

- Using the atrium to capture solar gain in winter to increase its ambient temperature
- Using thermal mass and shading in summer in a naturally ventilated atrium to reduce sol-air temperatures and reduce the host building's cooling load

However, designers face difficulties in predicting the atrium temperatures through the range of the building's climate changes and use pattern. Complex computer modeling techniques that study the dynamic performance of the building's materials in conjunction with the availability of internal and solar gains but also external climatic conditions help overcome these limitations (Mills, 1994).

A3.1.3 Natural Ventilation

As studied further below, atria provide optimum conditions for natural ventilation application. Atrium spaces are often used to induce air movement from the external facades to the inner face and subsequently exhaust that air through the atrium roof. Yet, natural ventilation is not always reliable so mechanical assistance is often provided for the supply and/or extract of air. For example in the case of an atrium building located in a city center filtering has to be applied to the air intake before it is supplied into the building. Furthermore, during hot spills the stack effect is often attenuated or even reversed so mechanical extract has to be provided to good air flow conditions inside the atrium (Mills, 1994). With the current climatic conditions the cooling capacity of natural ventilation is around 30-40 W/m^2 per day so natural ventilation strategies are limited to buildings with total internal gains of that magnitude (CIBSE AM 10, 2005).

A3.1.4 Plenum Space

Mills (Mills, 1994) characterises atria integrated into the engineering systems of a building as the most significant energy-efficient mode for atria in modern commercial schemes. Some of common examples of such opportunities are given below:

- Before entering the air-handling plant, fresh air drawn through the atrium is preheated by solar and internal heat gains (supply plenum)
- Heat flow from the adjacent occupied spaces is reduced by the conditioned buffer space provided by the exhausted from the building's air handling systems into the atrium stale air (exhaust plenum)
- A tempered buffer space is provided is provided by the 'dumping' of waste heat from the building into the atrium space, thus reducing heat losses and adding amenity value at no extra cost (heated buffer space)

Appendix B

Appendix B: TAS Results

Table 18 : Limiting U-value standards (W/m^2K)(Office of the Deputy Prime Minister, 2006 p. 17)

Element	(a) Area-weighted average	(b) For any individual element
Wall	0.35	0.7
Floor	0.25	0.7
Roof	0.25	0.35
Windows, roof windows, rooflights and curtain walling	2.2	3.3
Pedestrian doors	2.2	3.0
High usage entrance doors	6.0	6.0
Roof ventilators (inc. smoke vents)	6.0	6.0

Notes:

1 Excluding **display windows** and similar glazing. There is no limit on design flexibility for these exclusions but their impact on CO_2 emissions must be taken into account in calculations.

2 The U-values for roof windows and rooflights in this table are based on the U-value having been assessed with the roof windows and rooflight in the vertical position. If a particular unit has been assessed in a plane other than the vertical, the standards given in this Approved Document should be modified by making an adjustment that is dependent on the slope of the unit followng guidance given in BR 443.

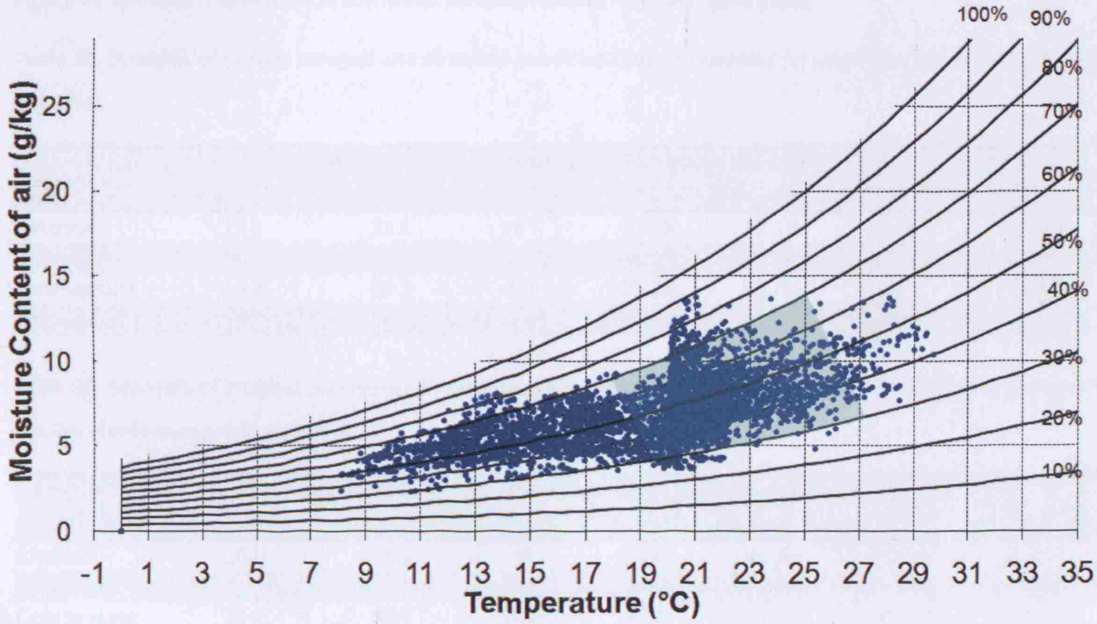

Figure 47. Psychrometric chart for cafe seating area for occupied hours yearly for the 'no plant room gains' scenario

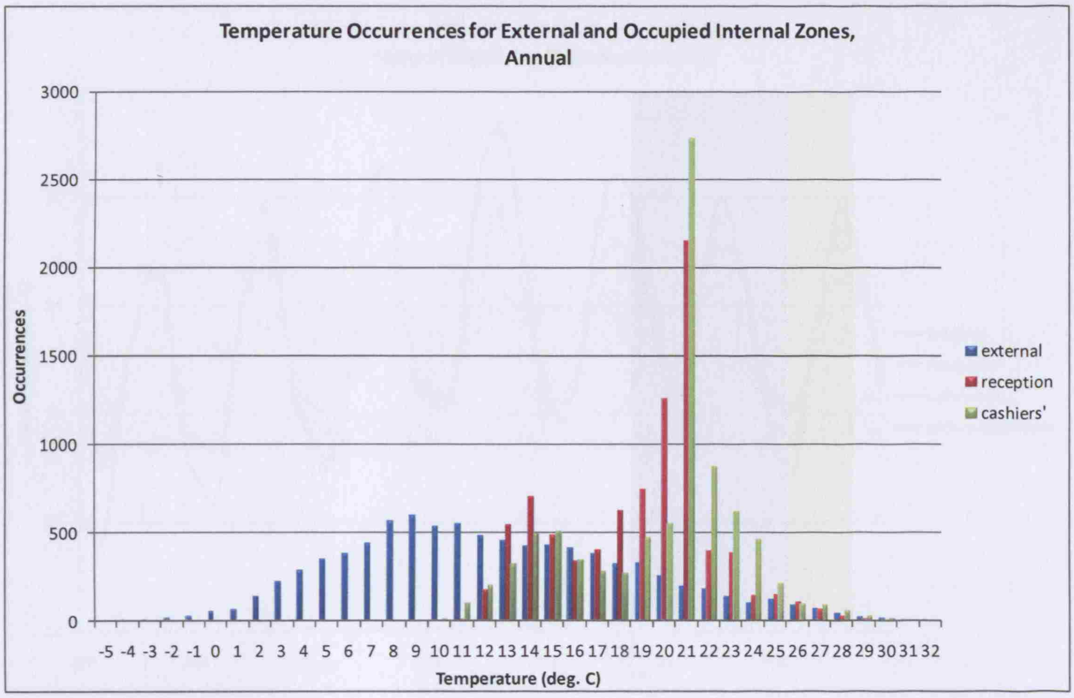

Figure 48. Annual temperature occurrences for external and main occupied areas

Table 19. Synopsis of annual internal and external conditions for all occupied hours of the 'no plant room gains' scenario

Annual, Occupied Hours (No Plant Room Gains)							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	13.9	31.1	-4.7	70.3%	22.0%	6.6%	1.5%
Reception	18.5	28.0	9.4	38.0%	56.8%	5.2&	0.0%
Cafe Seating	19.7	29.5	8.1	29.6%	63.7%	6.7%	0.9%
Cashiers'	19.8	29.5	7.9	29.2%	63.8%	7.0%	1.0%

Table 20. Synopsis of internal and external conditions for the occupied hours of the hottest monitored week for the 'no plant room gains' scenario

Hottest Week, Occupied Hours (No plant room gains)							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	26.6	31.1	18	0.0%	25.4%	76.4%	41.8%
Reception	25.7	28	20	0.0%	27.3%	72.7%	0.0%
Cafe Seating	26.2	29.5	20.3	0.0%	27.3%	72.7%	30.9%
Cashiers'	26.4	29.5	20.5	0.0%	25.5%	74.5%	34.5%

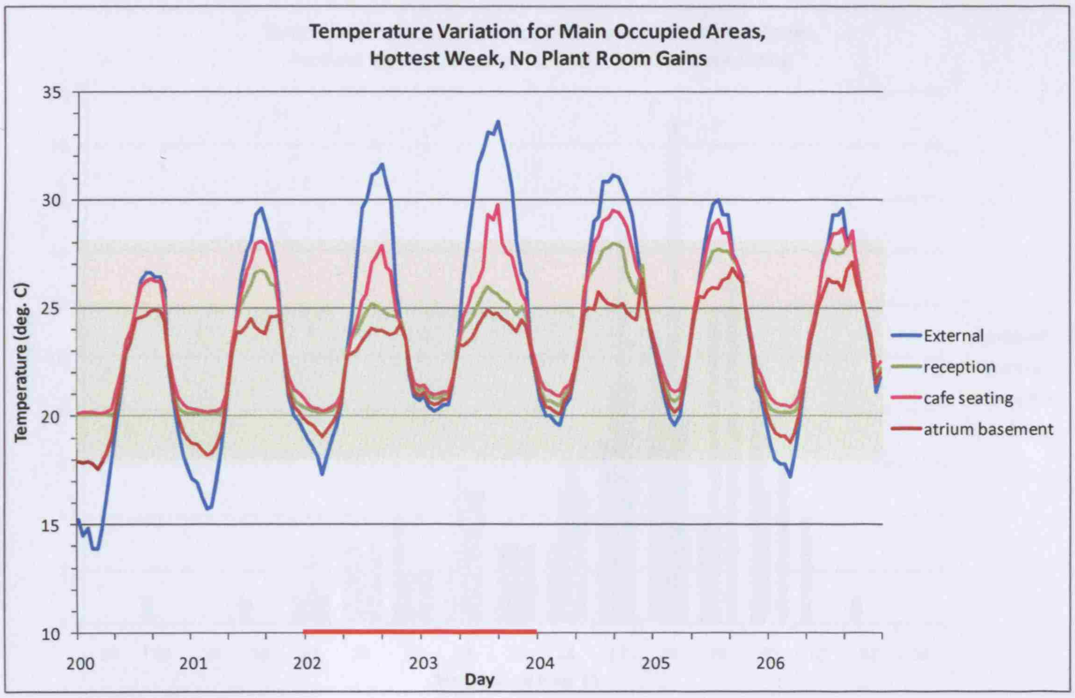

Figure 49. Diurnal temperature variation for main occupied areas for the hottest week of the 'no plant room gains' case – red line indicates the weekend

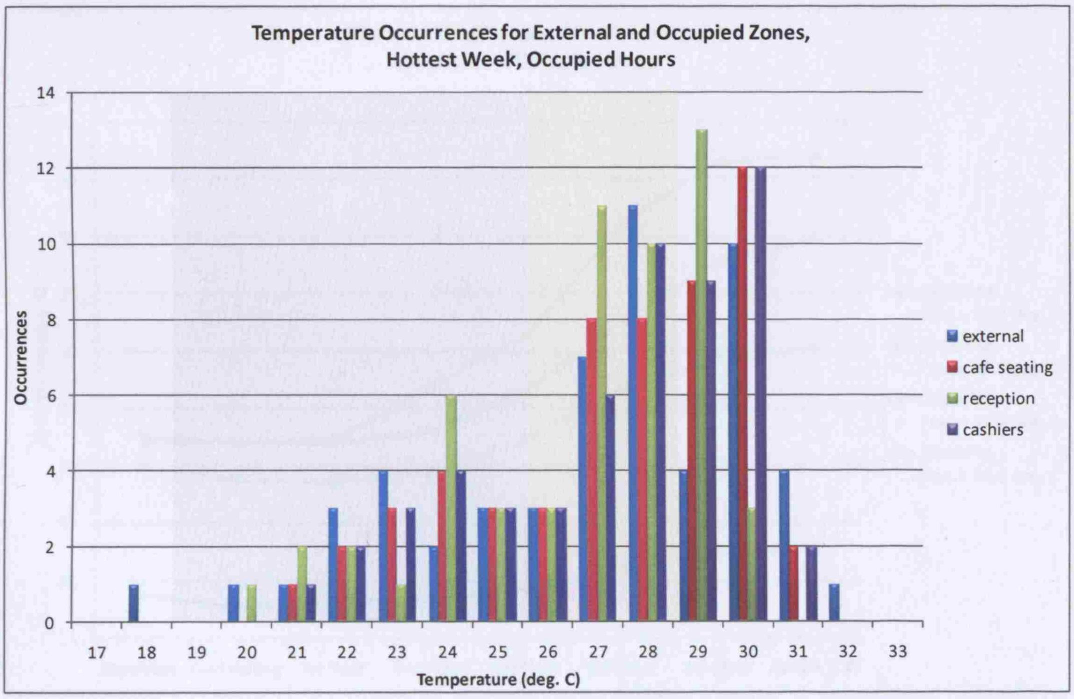

Figure 50. Temperature occurrences for the main occupied areas on occupied hours of the hottest week

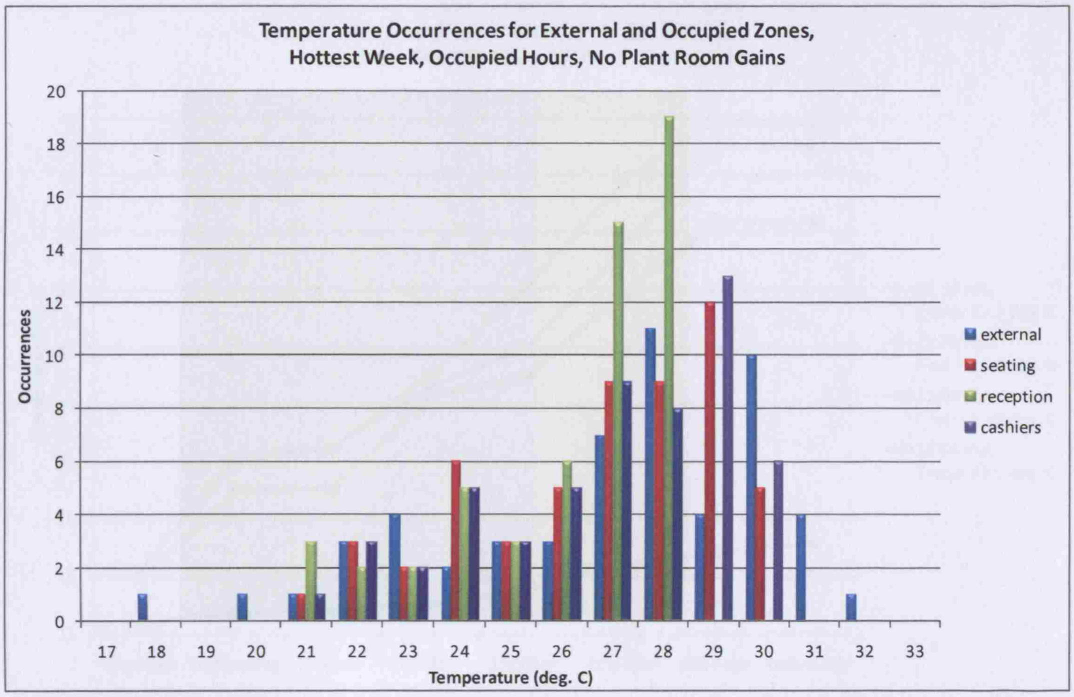

Figure 51. Temperature occurrences for the main occupied areas on occupied hours of the hottest week for the 'no plant room gains' scenario

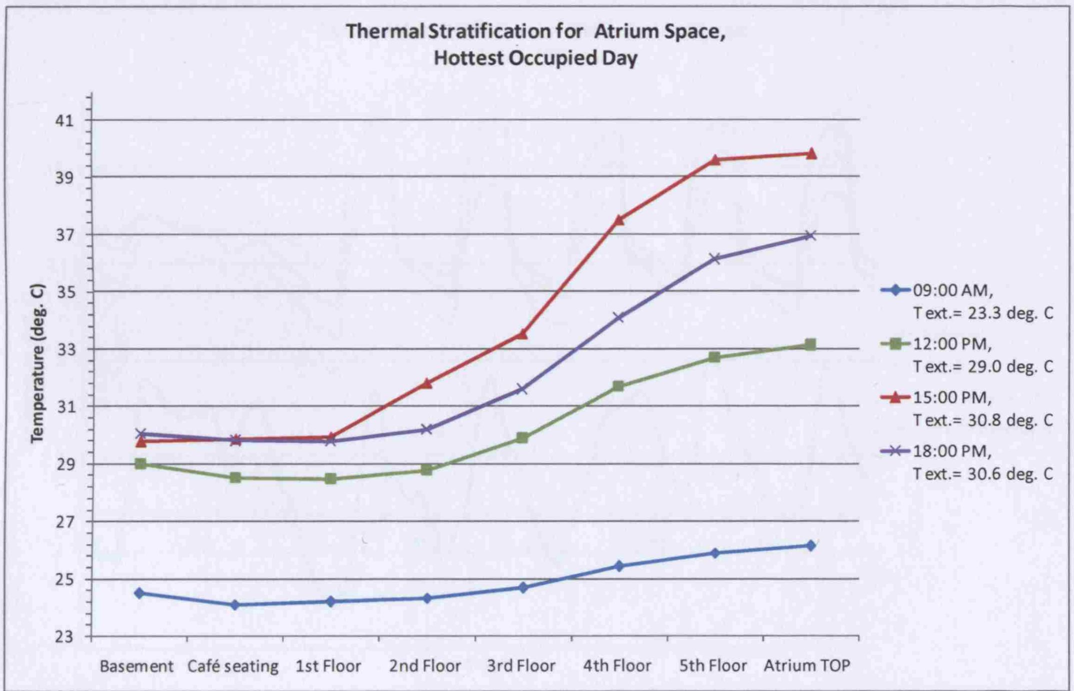

Figure 52. Thermal stratification in atrium space for different hours of the hottest occupied day

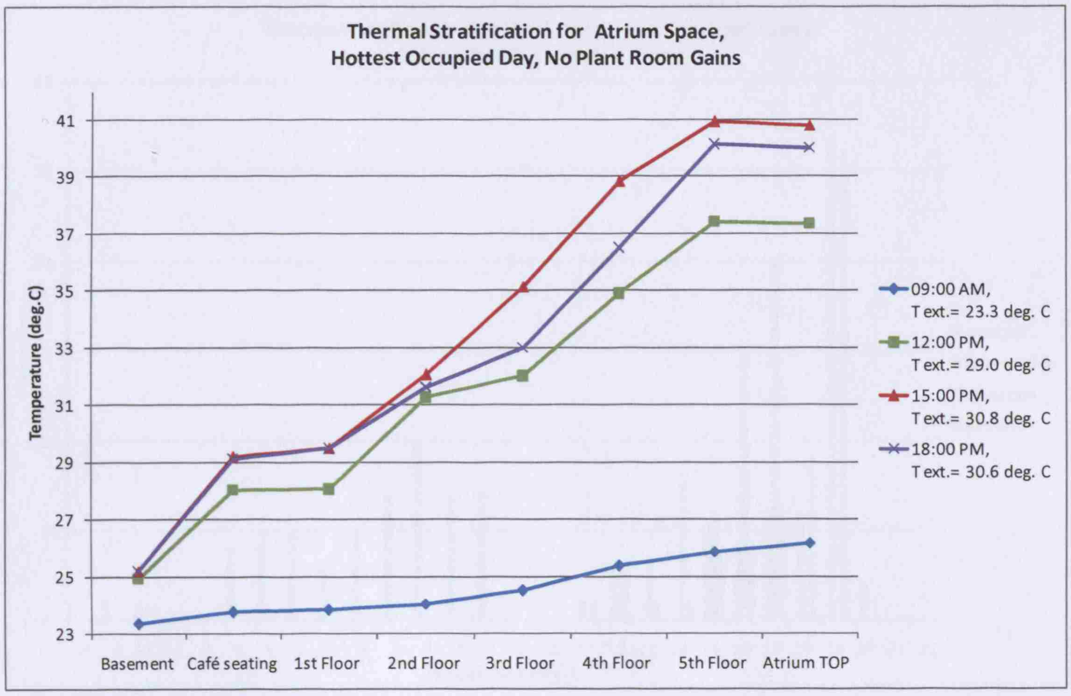

Figure 53. Thermal stratification in atrium space for different hours of the hottest occupied day for the 'no plant room gains' scenario

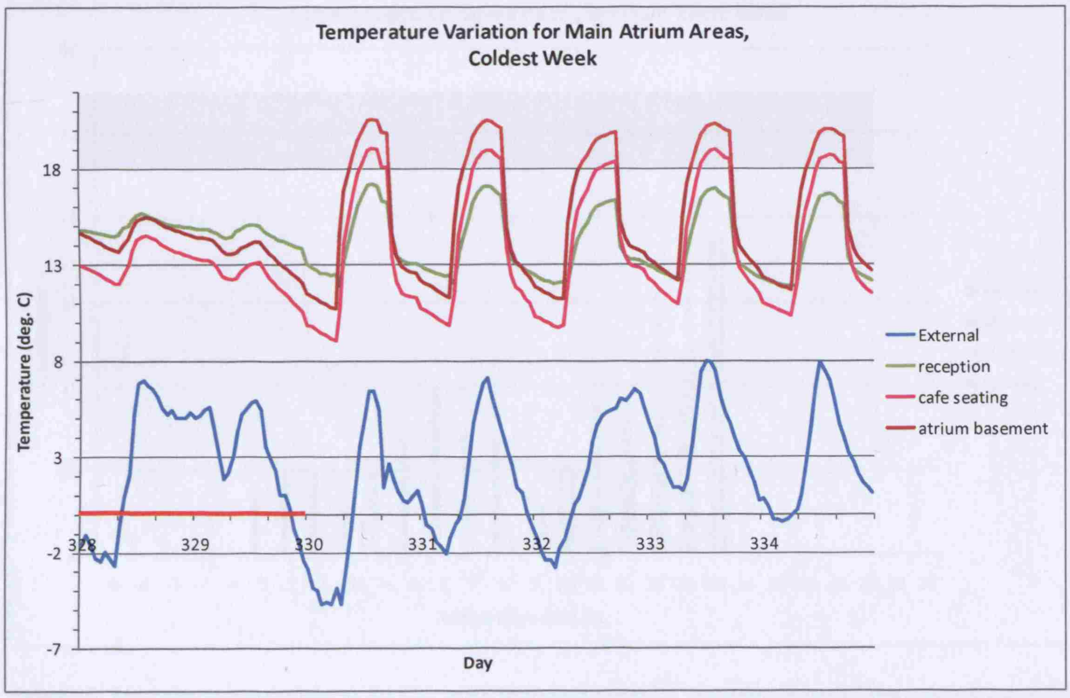

Figure 54. Diurnal temperature variation for main occupied areas for the coldest week (24th to 30th November)– red line indicates the weekend

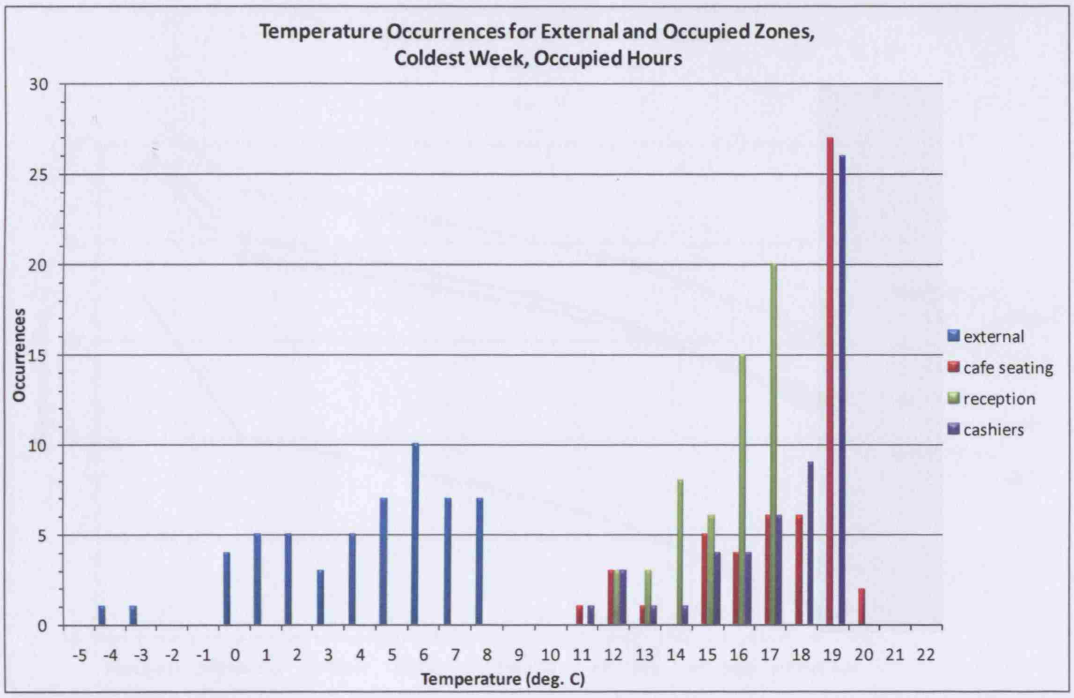

Figure 55. Temperature occurrences for the main occupied areas on occupied hours of the coldest week

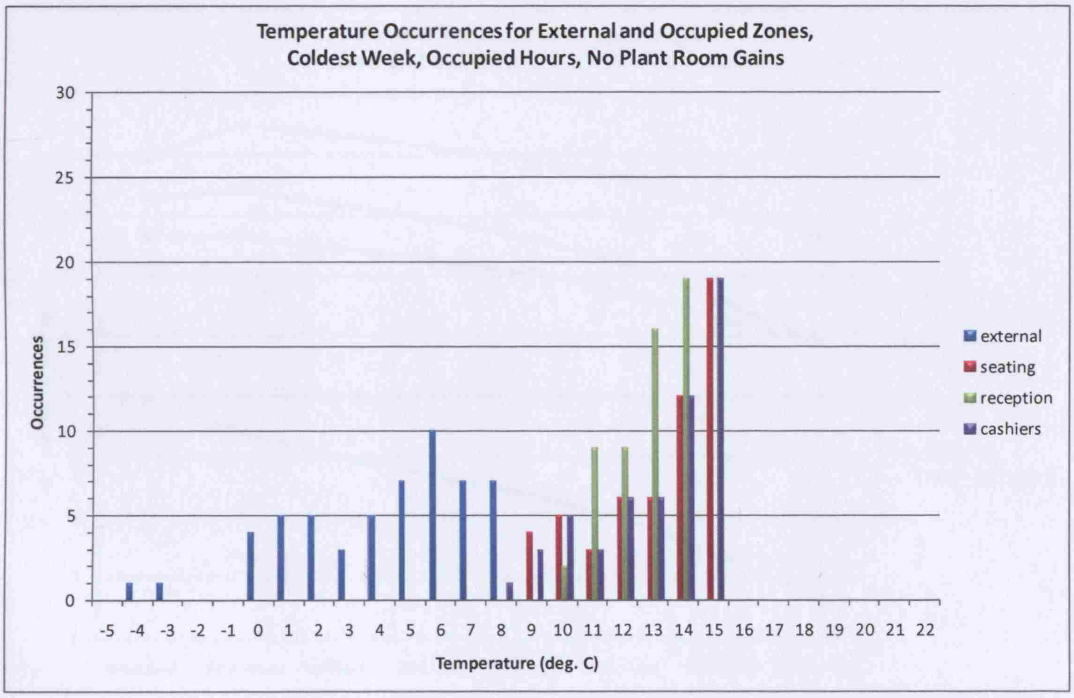

Figure 56. Temperature occurrences for the main occupied areas on occupied hours of the coldest week for the 'no plant room gains' scenario

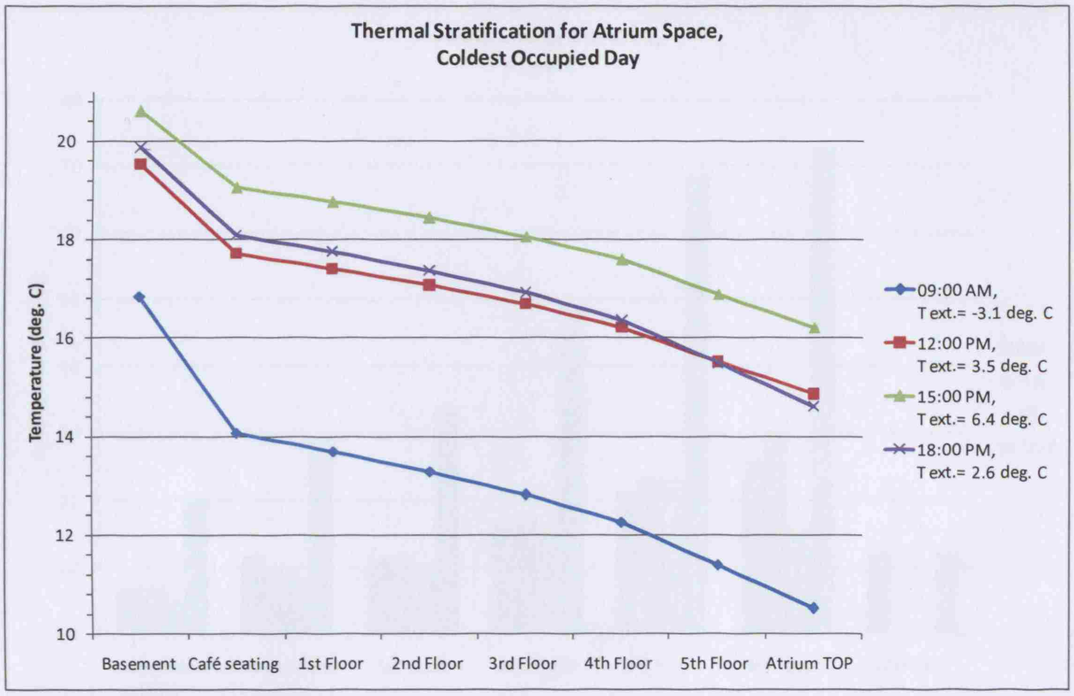

Figure 57. Thermal stratification in atrium space for different hours of the hottest occupied day

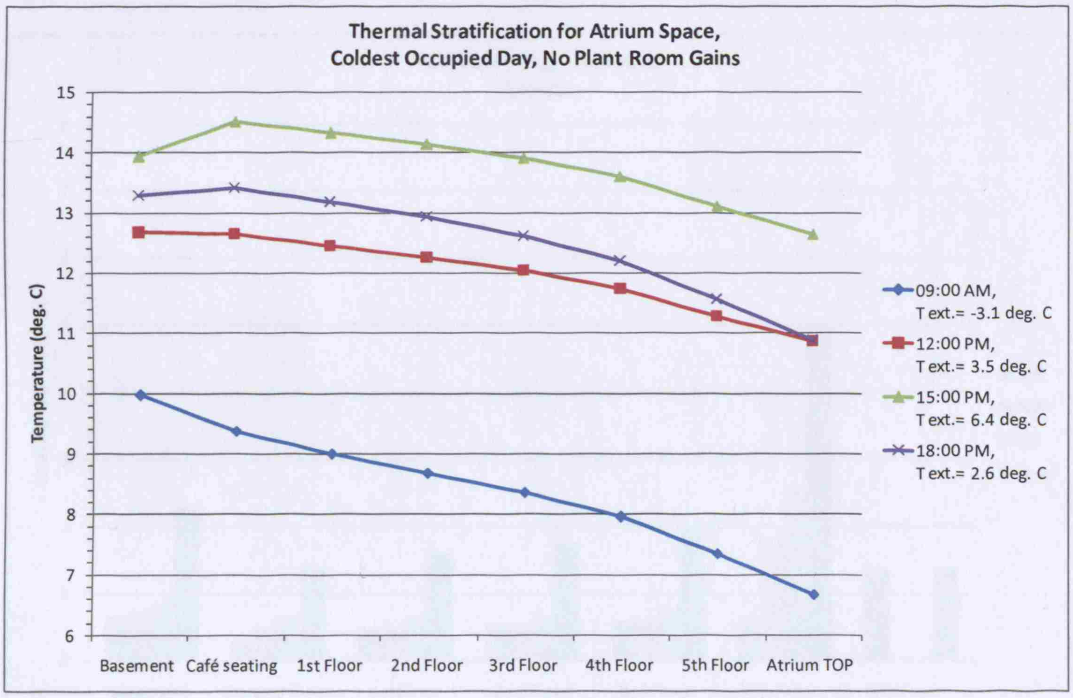

Figure 58. Thermal stratification in atrium space for different hours of the coldest occupied day for the 'no plant room gains' scenario

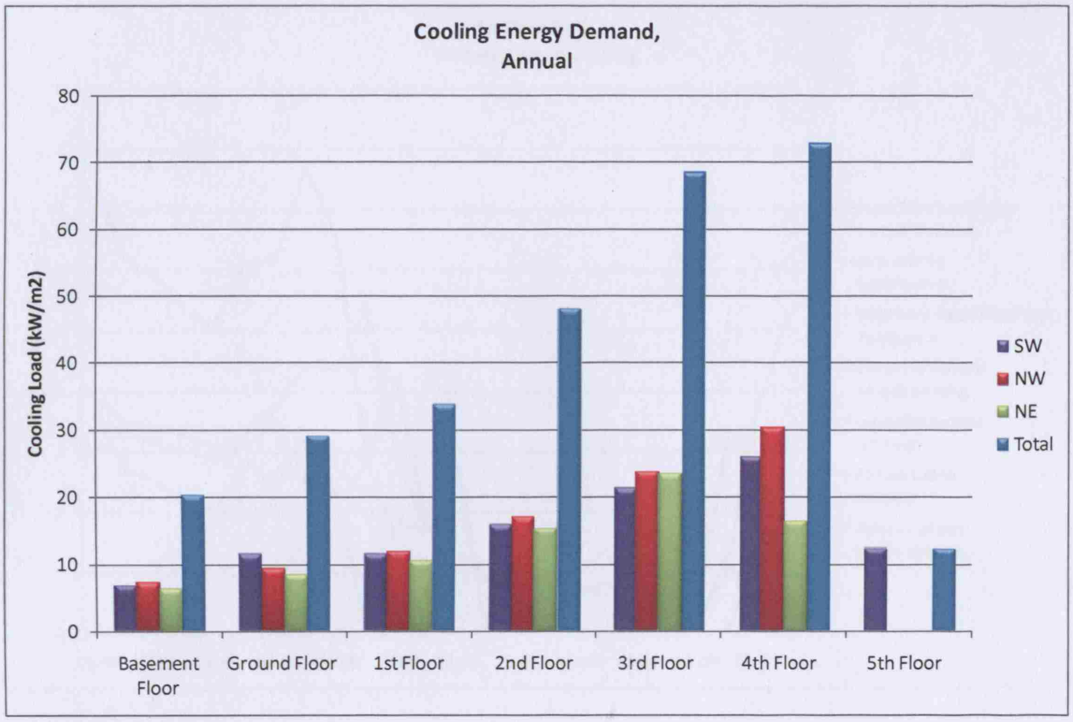

Figure 59. Annual cooling energy demand per floor and per orientation (TAS results)

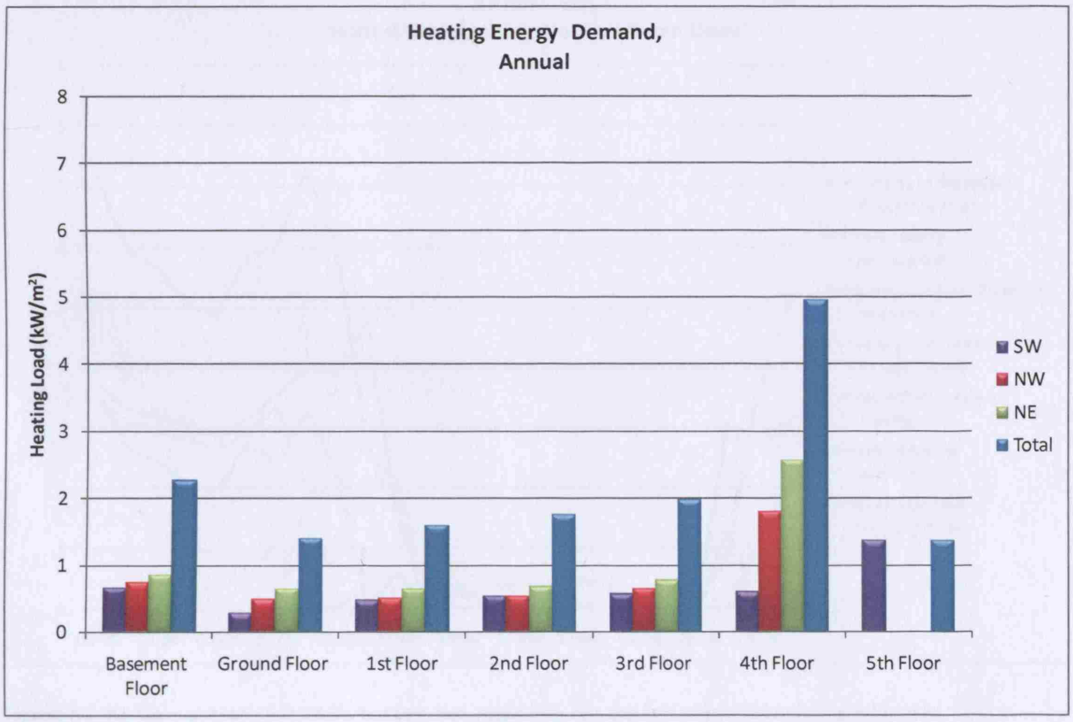

Figure 60. Annual heating energy demand per floor and per orientation (TAS results)

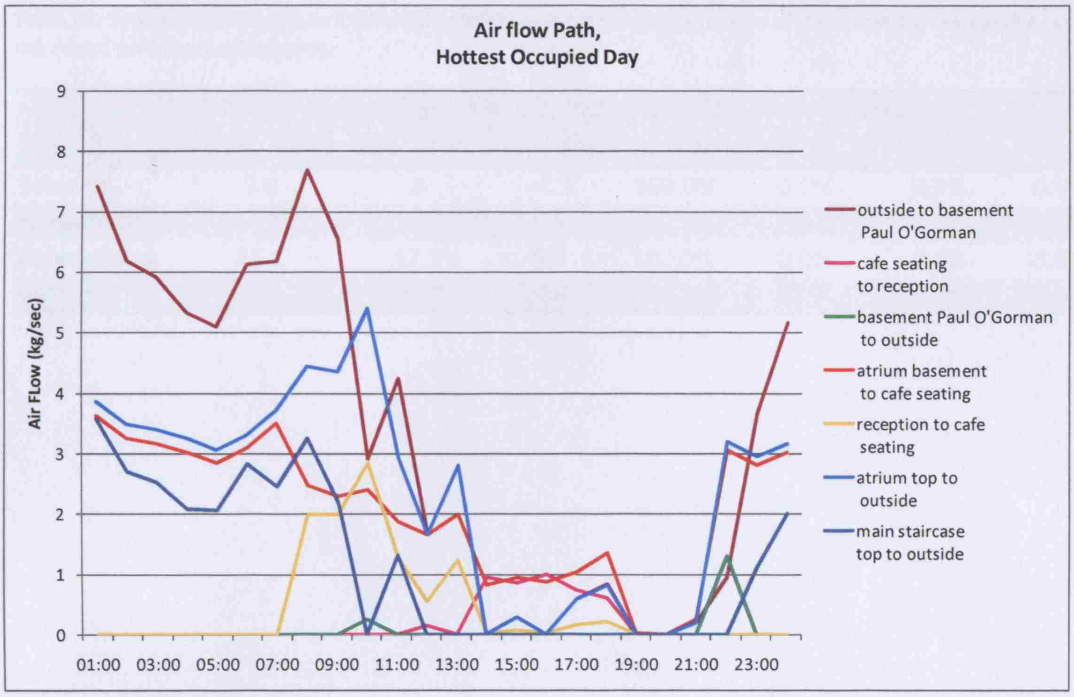

Figure 61. Air flow pattern for TAS's hottest occupied day

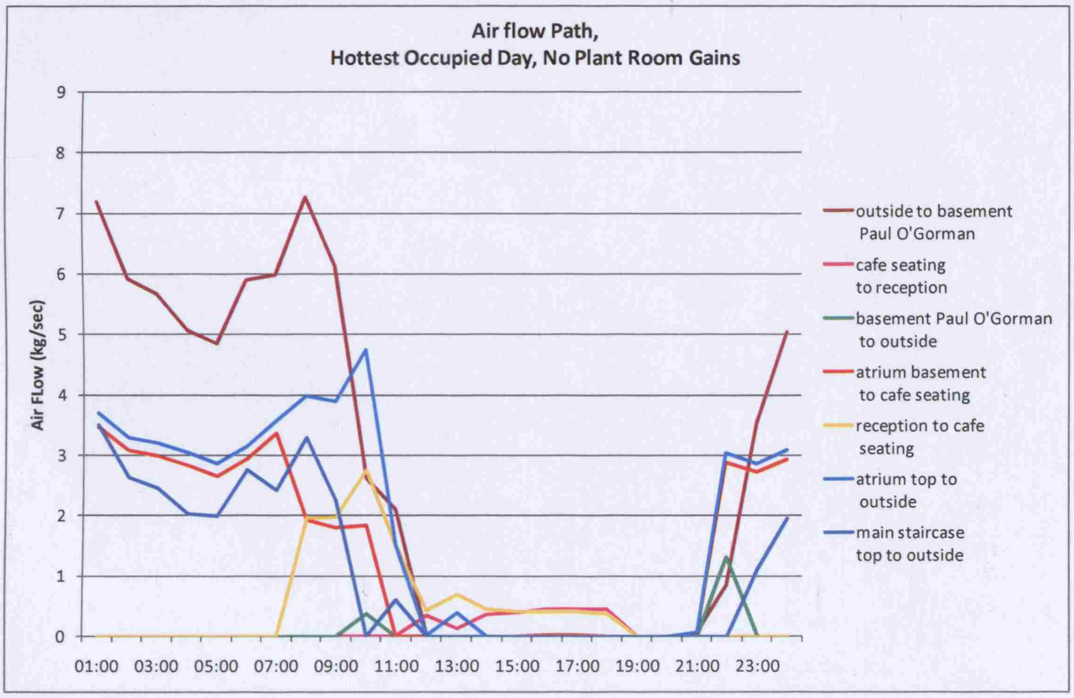

Figure 62. Air flow pattern for TAS's hottest occupied day for the 'no plant room gains' scenario

Table 21. Synopsis of internal and external conditions for the occupied hours of the coldest week for the case of the raised café protection border

Coldest Week, Occupied Hours, including cafe protection border							
Zone	average T (°C)	max T (°C)	min T (°C)	T<18 °C	18<T<25 °C	T>25 °C	T>28 °C
External	3.9	8	-4.7	100.0%	0.0%	0.0%	0.0%
Reception	14.2	15.8	9.9	100.0%	0.0%	0.0%	0.0%
Cafe Seating	15.1	17.3	9.4	100.0%	0.0%	0.0%	0.0%
Cashiers'	16.9	18.8	10.6	100.0%	0.0%	0.0%	0.0%

Appendix C

Appendix C: Monitoring & Related TAS Results

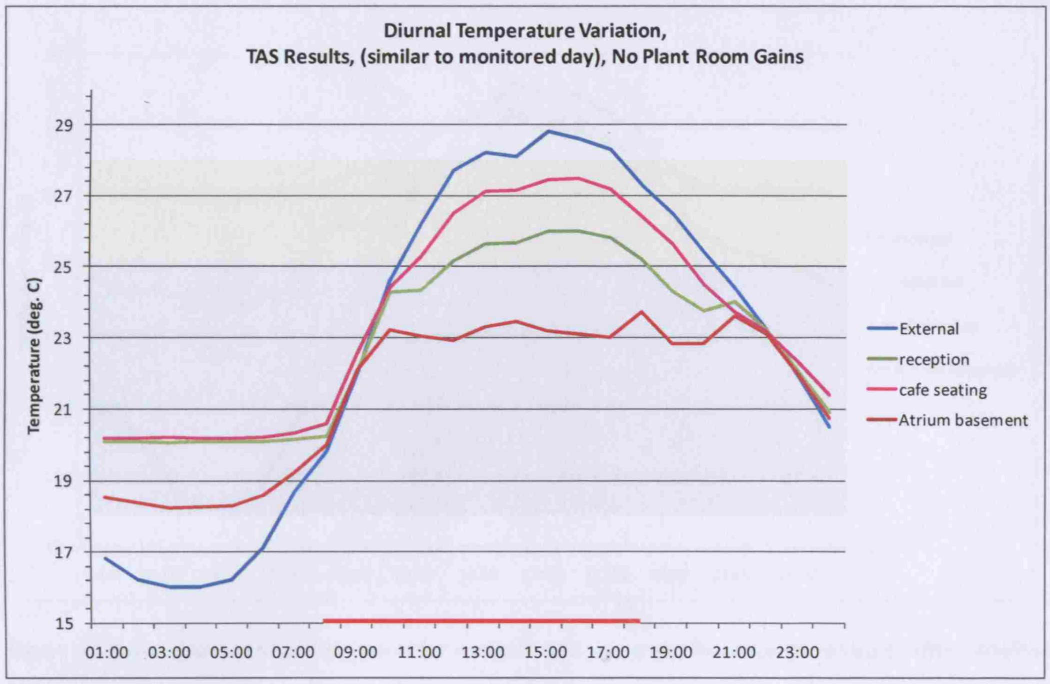

Figure 63. Diurnal temperature variation for external and key areas for a similar hottest monitored occupied day, obtained from TAS 'no plant room gains' simulation

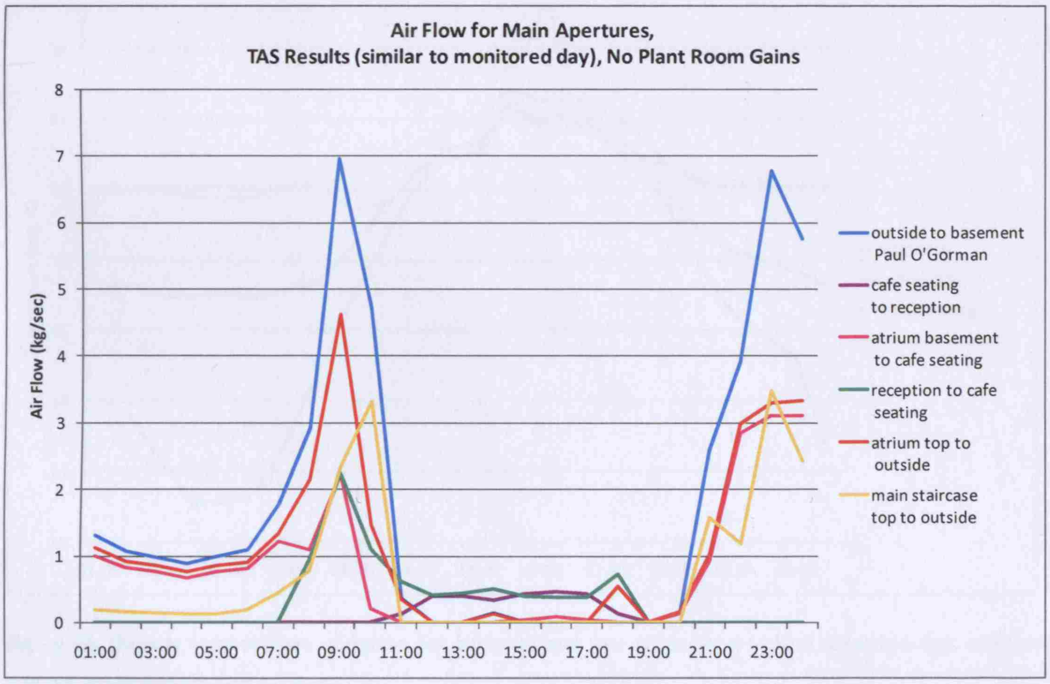

Figure 64. Air flow pattern for similar to hottest monitored occupied day obtained from TAS simulation for the 'no plant room gains' scenario

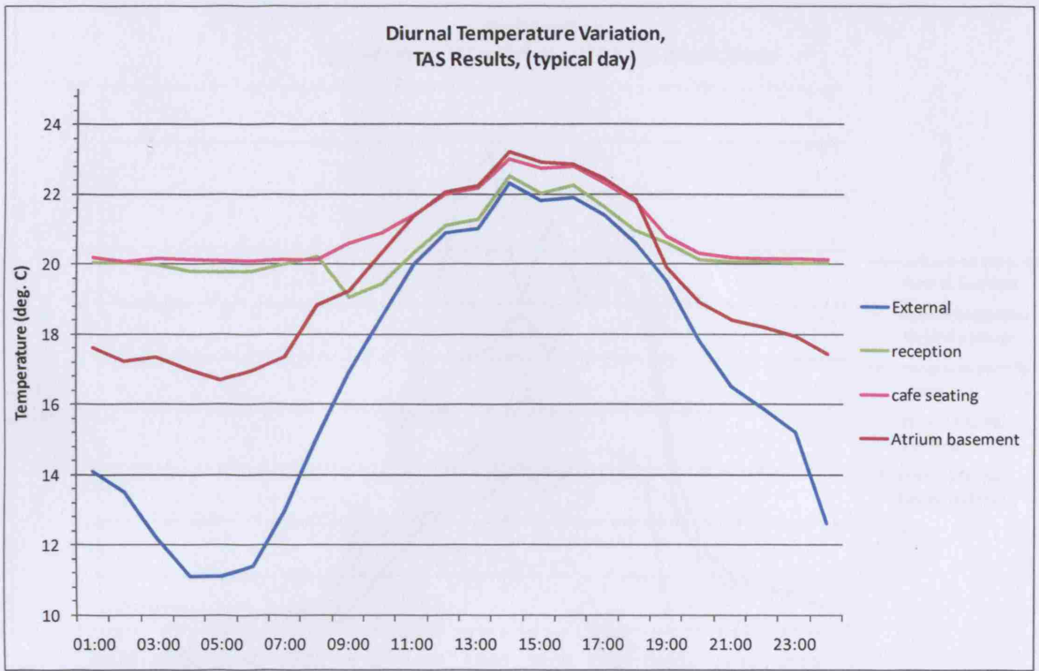

Figure 65. Diurnal temperature variation for external and key areas for a typical occupied day, obtained from TAS simulation

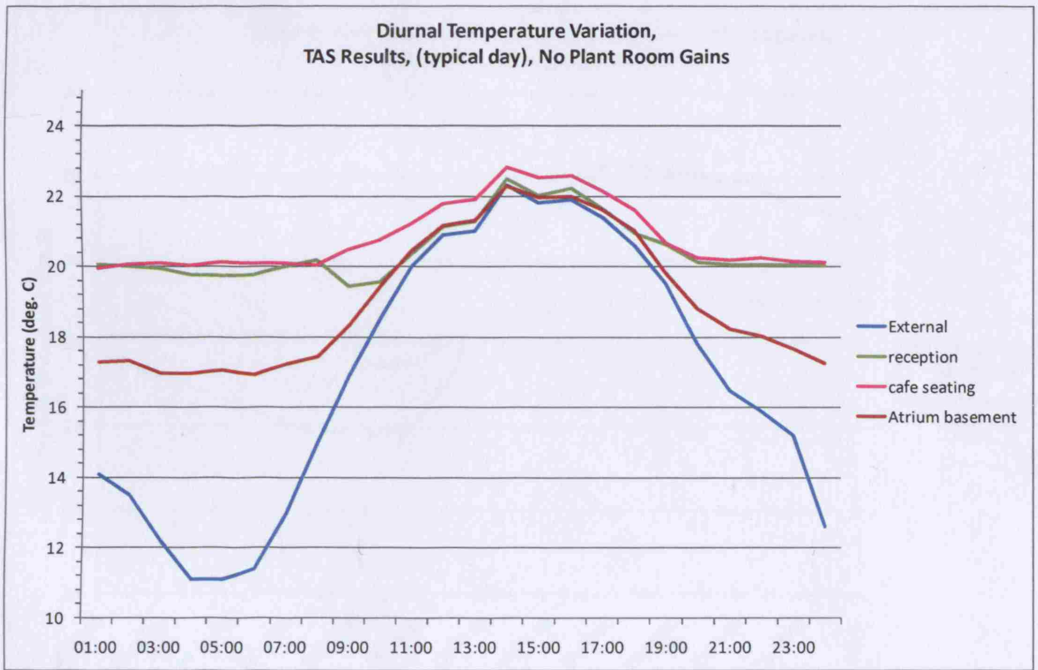

Figure 66. Diurnal temperature variation for external and key areas for a typical occupied day, obtained from TAS 'no plant room gains' scenario

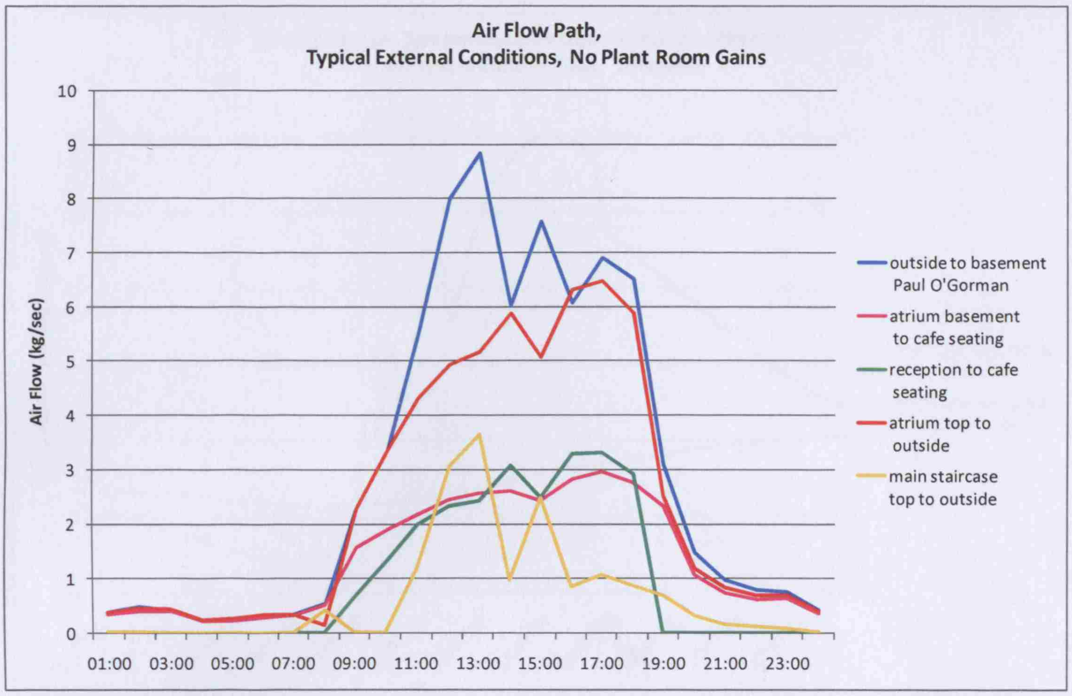

Figure 67. Air flow pattern for a typical occupied day obtained from TAS simulation for the 'no plant room gains' scenario

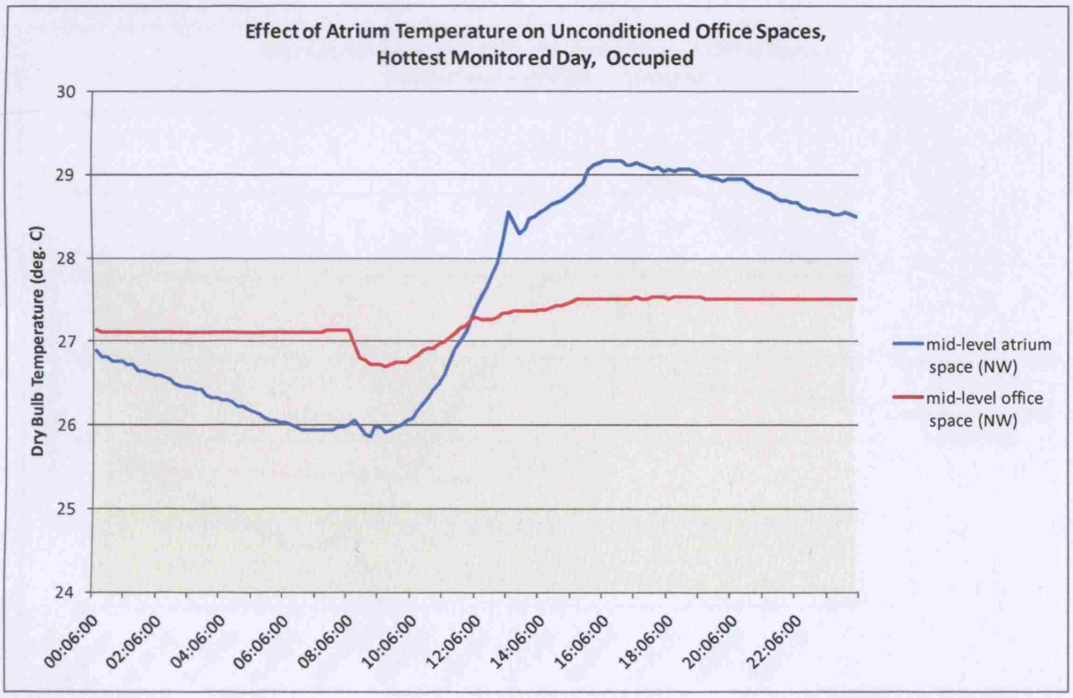

Figure 68. Comparison of temperature variation between the internal of a mid-level NW atrium office and mid-level NW atrium

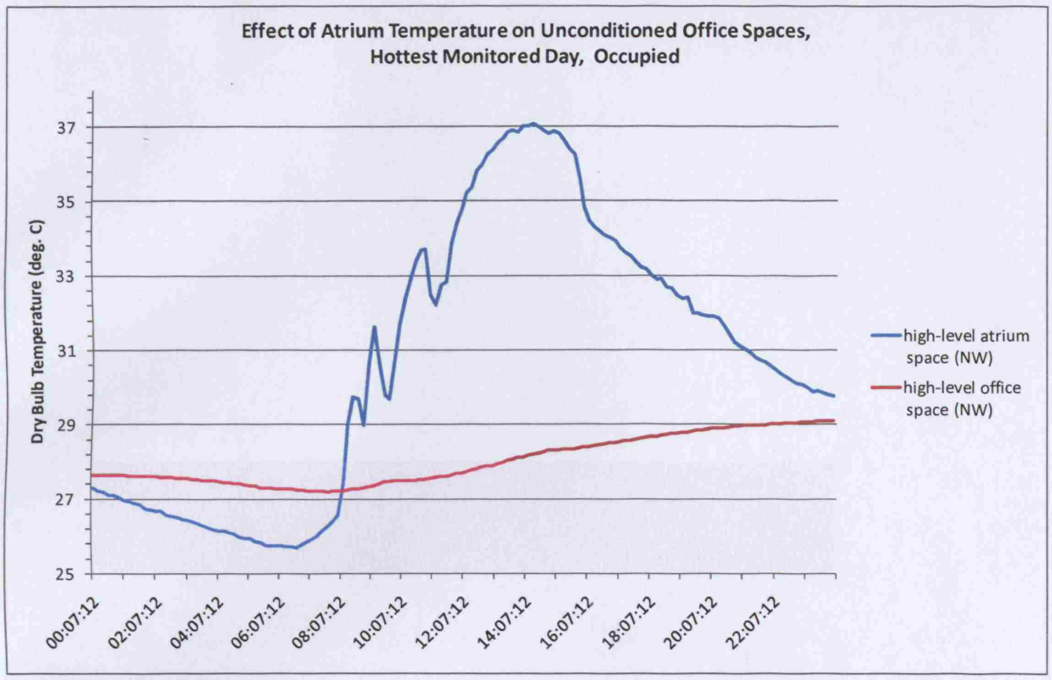

Figure 69. Comparison of temperature variation between the internal of a high-level NW atrium office and high-level NW atrium

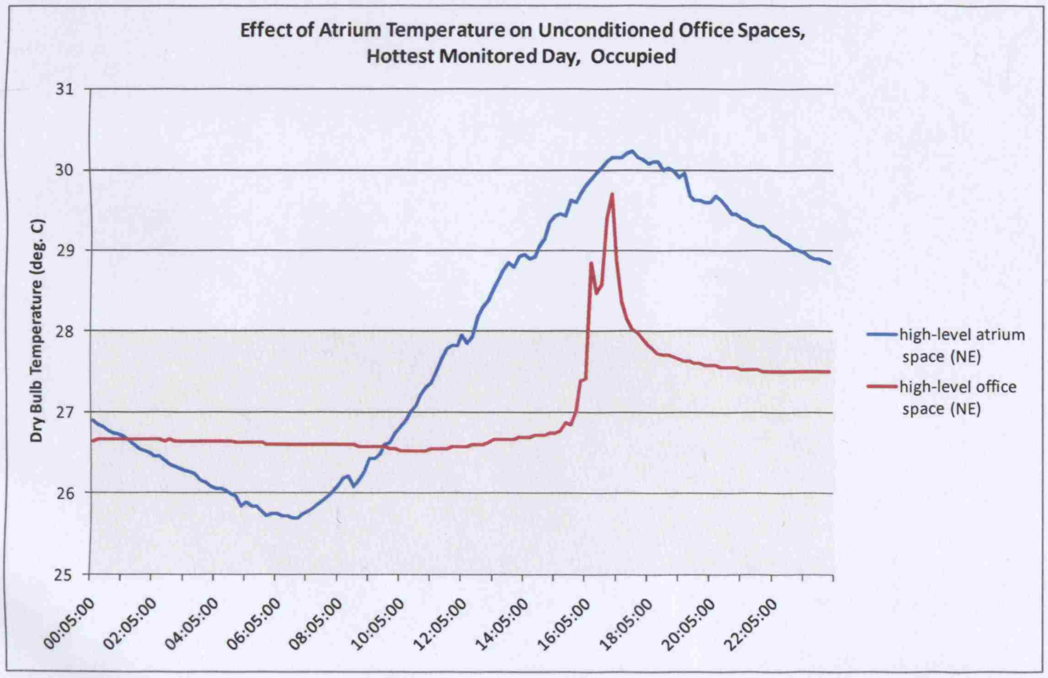

Figure 70. Comparison of temperature variation between the internal of a high-level NE atrium office and high-level NE atrium